Effects of snow cover manipulation and climate factors on the development of soil frost in forested boreal peatlands in Minnesota, USA

A THESIS

SUBMITTED TO THE FACULTY OF THE

UNIVERSITY OF MINNESOTA

BY

Hannah Cecilia Friesen

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

Robert A. Slesak, Adviser

Diana L. Karwan, Co-Adviser

Randall K. Kolka, Committee Member

August 2019

Acknowledgements

I express my deepest gratitude to the following people, without whom I would never have been able to successfully implement and complete this project: Beckie Prange, Kyle Gill, Rachael Olesiak, Lane Johnson, Anne Gapinski, Deacon Kyllander, Katy Johnson, Sara Kelso, Lucy Rose, Alan Toczydlowski, Odin Holmes, and Kevin and Terri Friesen for their assistance in installing and monitoring my experimental plots, as well as collecting data, removing snow cover, and taking numerous measurements; Lucy Rose, Ethan Pawlowski, and Zac McEachran for assistance in data processing and analysis; and my advisers, Drs. Robert Slesak and Diana Karwan, as well as my committee member, Dr. Randall Kolka, for their patience, guidance, and assistance with this project from its inception to its conclusion. This research was supported by the Minnesota Forest Resources Council, the Environmental and Natural Resources Trust Fund, USDA Forest Service, and the University of Minnesota Department of Forest Resources.

Abstract

Black spruce (*Picea mariana*) peatlands play an important ecologic and economic role in the temperate-boreal region of North America, providing a valuable timber resource in addition to performing important ecosystem functions. Climate models project decreases in the amount of snowfall throughout the temperate-boreal region by 2100, as average wintertime temperatures increase. While the effect of a loss of snow cover on soil frost dynamics has been well-studied in mineral soil environments through the use of snow removal techniques, similar analysis on decreased snow cover in peatland soils is less common and related effects unclear. To fill this gap in understanding, we used a paired-plot experimental design to assess the effect of snow removal on soil temperature and frost development at six forested peatland sites in northern Minnesota, USA, during the winters of 2017-2018 and 2018-2019. Treatments were either 1) removal of snow throughout the winter, or 2) ambient snow conditions. During both years of the study, there was a significant effect of snow removal by mid-winter that continued into late winter and spring, where removal of snow correlated with increased soil frost depth and colder soil temperatures, as compared to plots with ambient snow cover. Following the first winter of the study, it was found that soil frost persisted much later in snow removal plots, and snow removal plots had colder soils through much of the summer growing season. In addition, during the frozen season, soil temperatures in the removal plots were highly responsive to air temperature fluctuations to depths of 20 cm or more, resulting in increased variability in temperature, whereas the ambient snow cover soils exhibited little fluctuation and maintained temperatures near 0° C for much of the winter season. These results indicate that predicted changes to the amount and form of wintertime precipitation in the temperate-boreal zone may result in increased development of soil frost in forested peatland systems. However, the increased reactivity of soil temperature to air temperature fluctuations may offset the effect of decreased snow cover if average winter air temperatures are higher, as currently predicted.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

CFC: Cloquet Forestry Center

HWRC: Hubachek Wilderness Research Center

MEF: Marcell Experimental Forest

FDD: Freezing Degree Day

TDD: Thawing Degree Day

CO_2: Carbon Dioxide

CH_4: Methane

Effects of snow cover manipulation and climate factors on the development of soil frost in forested boreal peatlands in Minnesota, USA

Overview

Forested peatlands are one of the defining landforms of the boreal region. These systems provide important ecosystem services and economic opportunities, and may be uniquely vulnerable to climate change, particularly on winter season processes. The boreal region in which these peatlands are largely found has historically experienced long winter seasons with cold air temperatures, deep snow accumulation, and seasonal soil frost development. Changes to these winter conditions could have cascading effects on peatland hydrology and decomposition, factors strongly related to the ability of peatlands to sequester carbon (Dunn et al., 2007; Huang et al., 2017; Groffman et al. 1999; Groffman et al. 2001; Xu et al., 2018; Joosten et al., 2012; Yu et al., 2011). In addition, the economic value in forested peatlands lies largely in the ability of the forest industry to access valuable pulpwood species, such as black spruce (*Picea mariana*) and tamarack (*Larix laricina*), which are often the dominant species in these systems (Wright et al., 1992; Zhang & Morgenstern, 1995). This access depends upon the development of sufficient soil frost to hold the heavy equipment necessary for timber harvest to occur; changing winter climate, including warmer air temperatures and decreased snow accumulation, could impact the development of frost, with ramifications for management accessibility.

Because of their importance to the boreal region from both an economic and ecological perspective, a greater understanding of how changing winter conditions will affect peatlands is necessary. While several studies have previously used snow cover manipulation to mimic a future with decreased snow accumulation, these studies have largely been conducted in upland mineral soil systems (Decker et al., 2003; Hardy et al., 2001; Hart & Lull, 1963; Groffman et al. 1999; Groffman et al., 2001). Compared to peatlands, soil moisture conditions in upland mineral soil environments are drier and less likely to produce concrete frost, and therefore the results from snow-removal studies in these systems may have limited applicability to organic peatlands. The research presented in this thesis aims to fill this knowledge gap through the use of snow cover manipulation on plots in in forested peatlands to better understand how decreased snow cover, a likely outcome of climate change across the boreal region, may affect frost development in these systems. Chapter 1 describes the experimental methodology developed for this study and summarizes results from two winter seasons (2017-2018 and 2018-2019). We observed colder soils, deeper and more persistent soil frost, and faster development of soil frost under snow removal conditions than under conditions of ambient snow cover. We also observed that soil temperature under snow removal conditions was closely related to fluctuations in air temperature during the frozen season, while under ambient snow cover conditions, soil temperature was largely stagnant through the winter. The results observed in this study, while generally consistent in pattern with those observed in studies in mineral soil environments, indicate that the magnitude of the effect of snow removal may be greater in peatlands than uplands, with colder soils and deeper, more persistent frost than was observed in previous studies. While some difference in the magnitude of the results may be attributed to differences in methodology and/or climate from previous studies, it may also be a result of the unique hydrology of peatlands. These results provide additional insight into how northern peatland systems may react to climate change and contributes to the field of research focusing on climate change effects on boreal ecosystems.

Introduction

Northern peatlands play an important ecological and economic role globally. Peatlands cover more than four million km^2 of the earth's terrestrial surface, mostly concentrated in the boreal regions of Canada, Scandinavia, Russia, and northern portions of the United States (such as Alaska and the Lake States) (Xu et al., 2018). Minnesota alone contains over 24,000 km^2 of peatlands, over 10% of the state's total land area (Wright et al., 1992). Peatlands are defined as regions containing a relatively thick surface layer (at least 30-40 cm) of undecomposed or partially decomposed organic matter that often dates to several thousand years old (Limpens et al., 2008; Frolking et al., 2011). Peatlands generally form in saturated, anaerobic environments, where decomposition is greatly reduced and organic matter accumulates over time (Dunn et al., 2007). These conditions, combined with cool temperatures typical of the boreal zone, resulted in the development of large terrestrial carbon reservoirs which contain approximately 33% of the global soil carbon pool in only 3% of the global land surface area (Limpens et al., 2008; Frolking et al., 2011; Xu et al., 2018). They also support habitat for unique and rare flora and fauna, providing an important source of biodiversity in both northern and global ecosystems (Xu et al., 2018). In addition to providing numerous ecosystem services, northern peatlands are also an economically valuable resource. Many of the bogs and fens that make up these peatlands contain commercially viable tree species such as black spruce (*Picea mariana*) and tamarack (*Larix laricina*), which are valued throughout the boreal region as pulpwood and timber sources (Wright et al., 1992; Zhang & Morgenstern, 1995). In Minnesota, over 93% of spruce harvested is utilized for pulpwood due to its exceptional quality fiber (Division of Forestry, 2019).

Changing climate, particularly in the winter months, may have profound ramifications for peatlands, affecting the ecological and economic roles they play in northern ecosystems. Several wintertime processes, including snow accumulation, soil frost development, and seasonal thaw, have a strong influence on peatland hydrology and soil temperature. These changes could affect several ecosystem services provided by peatland systems (e.g., sequestration of carbon) because of the impact of winter processes on water table, length of frost season, growing season, and decomposition rates (Dunn et al., 2007; Huang et al., 2017; Groffman et al. 1999; Groffman et al. 2001; Xu et al., 2018; Joosten et al., 2012; Yu et al., 2011).

Boreal peatlands can alternate between acting as a weak carbon sink and a carbon source to the atmosphere, they have historically provided long-term storage of terrestrial carbon, since over long time scales, net primary production tends to be greater than the rate at which organic matter is decomposed in these systems (Dunn et al., 2007; Frolking et al., 2011; Xu et al., 2018; Yu 2011; Yu et al., 2011). However, previous studies have found that loss of permafrost in boreal peatlands is associated with increased CO_2 and

CH_4 flux to the atmosphere, and loss of seasonal frost in lower latitude peatlands may have similar outcomes (Turetsky et al., 2002). Additionally, potential climate change effects on wintertime temperatures and snow patterns is also of high concern to forest resource managers and forest industry, as cold season (i.e., frozen soil) harvests are used to access forest resources in areas where soils are moist (Kolka et al. 2012; Shoop, 1995). Due to their saturated organic soils, sufficient soil frost is necessary to support the heavy machinery used in harvest operations (Shoop, 1995). Research has indicated that frost depths of 25-50 cm may be necessary to hold most heavy harvest equipment in peatland systems (Shoop, 1995). Climate change may negatively impact access to forest resources in boreal peatlands should rising temperatures and changes in snowfall adversely affect soil frost development in these systems.

Because of their proximity to the prairie border, Minnesota's peatlands are considered a useful "bellwether" of potential climate change effects on peatlands in the larger boreal region (Wright et al., 1992; Handler et al., 2014). In this region, climate change is expected to increase winter air temperatures and decrease snow fall, as more precipitation is expected to fall as rain rather than snow (Kellomäki et al., 2010; Handler et al., 2014). Many climate change models predict disproportionately warmer winter temperatures over the next several decades, which could have drastic impacts on the development of soil frost. By the end of this century, model simulations estimate a drop in the average number of days with soil frost (by ~30 from a base average of ~160 in northern Minnesota) and decreased total frost depth (~40%) as air temperatures rise (Henry, 2008; Kellomäki et al., 2010; Handler et al., 2014). These anticipated changes are supported by observations over the past several decades which have shown increased warming (0.7°C per decade since 1961) during the winter months and a lengthening of the growing season due to earlier spring thaw (Dymond et al., 2014; Sebsestyn et al., 2011).

One method by which researchers have attempted to study the impact of changing winter conditions on ecosystem processes is through the use of snow removal techniques, simulating a future with less snow cover. Of the few snow removal studies to date, most have been conducted in upland hardwood forest sites with mineral soils (Decker et al., 2003; Hardy et al., 2001; Hart & Lull, 1963; Groffman et al. 1999; Groffman et al., 2001). These studies found that decreased snow cover results in colder soils and increased depth of soil frost, which is associated with changes in carbon and nutrient cycling (Decker et al., 2003; Hardy et al., 2001; Hart & Lull, 1963; Groffman et al. 2001). However, because these studies were conducted in temperate ecosystems with mineral soils, their applicability to boreal peatland systems may be limited, because peatland organic soils are typically much colder and wetter, factors that can have implications for frost development due to the thermodynamic conductivity of water in saturated soils.

Here, I present research findings that assess how changing winter conditions will affect soil frost development in peatlands using snow manipulation in a paired plot experimental design in which snow was allowed to accumulate on one plot throughout the winter season and was removed from the other. This research design was based on similar studies conducted on upland forest sites (Groffman et al., 1999; Groffman et al., 2001; Hardy et al., 2001; Decker et al., 2003; Hart & Lull, 1963). My main objective is to quantify the relationships among air temperature, snow depth, soil temperature, and soil frost depth in forested peatland systems. I also explored techniques by which soil frost depth may be estimated from easily-measurable proxy variables, such as air temperature and cumulative freezing days. I hypothesized that removal of snow cover would result in colder soils and deeper soil frost development under average winter weather conditions than in plots with ambient snow cover, consistent with the results of previous studies. Determining the factors which moderate the development of soil frost in peatlands will be important to better understand how these relationships may be affected by climate change, both for impacts on forest management as well as potential hydrological and ecological changes in these systems.

Methods

Site Description

The study was conducted in Minnesota, USA, at six sites across three locations in the northern portion of the state: the Cloquet Forestry Center (CFC), Hubachek Wilderness Research Center (HWRC), and Marcell Experimental Forest (MEF) (*Figure 1*). These research forests are all located in the northeastern region of Minnesota and compose an ecosystem gradient, with CFC containing a mixture of boreal species and temperate northern hardwoods, while MEF and HWRC are dominated by boreal vegetation. Dominant tree species included black spruce (*Picea mariana*) at all sites, tamarack (*Larix laricina*) at the western CFC site, and mixed wetland species including

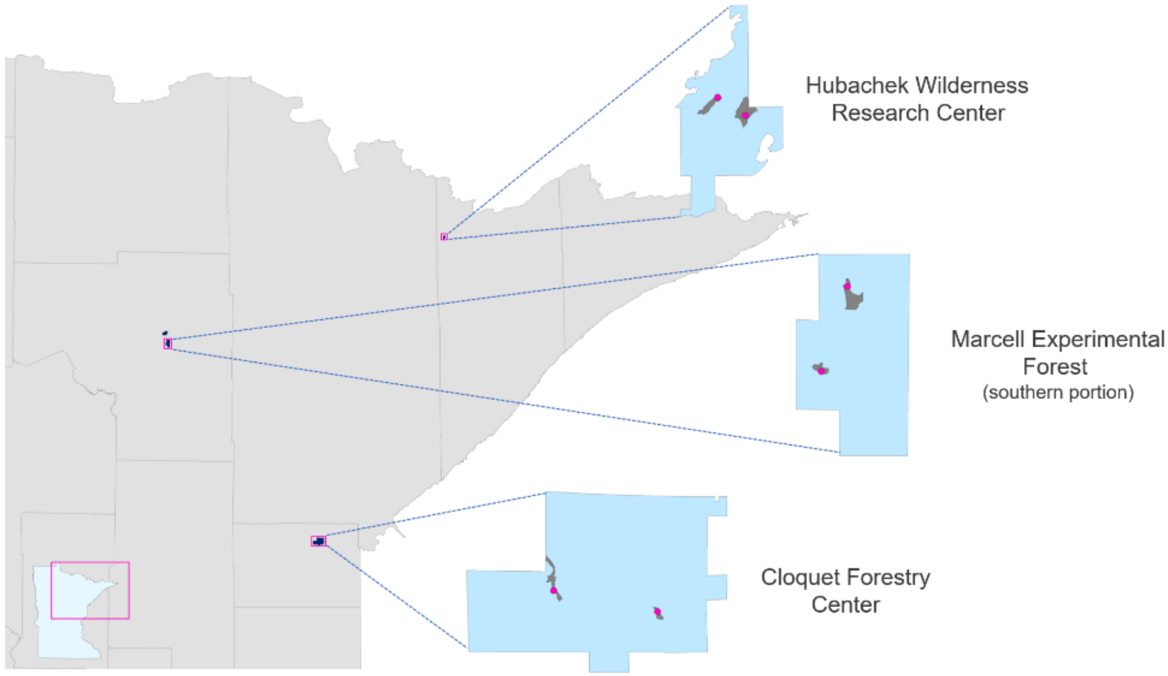


Figure 1: Research site locations in Northern Minnesota. Plot locations are represented by pink dots on the expanded forest maps. The dark grey areas on the expanded forest maps are the approximate areas of the peatland systems in which the research sites were installed. These sites represent an ecosystem gradient across the northeaster arrowhead region of Minnesota.

alder (*Alnus spp*.) and bog birch (*Betula pumila*) at the northern MEF site. This region generally has a moist and cool climate, with average annual precipitation of 71 to 81 centimeters and mean annual temperatures of 2.8 to 4.4°C across the region (Minnesota Department of Natural Resources, 2017). About one-third of the total annual precipitation in northern Minnesota is due to snowfall, with a common snow accumulation season of November to April (Sebestyn et al., 2011). Wintertime average temperatures range from -12.8 to -10.6°C (Minnesota Department of Natural Resources, 2017). All of the research forests contain peat-rich bogs and/or fens within their boundaries; the research sites for this study are located within these forested peatland systems. Sites were selected based on meeting the following criteria: soils dominantly composed of organic soil or peat; forested, with a canopy dominated by black spruce of harvestable size (diameter class of

5.0 to 8.9 cm); few trees, seedlings, or other large obstacles within plot areas for ease of snow removal; and ease of accessibility during winter months for timely removal of snowfall. Of the sites selected, five are classified as bogs, with one site classified as a fen (the northern MEF site, MEF-2). Site characteristics are summarized in *Table 1* and *Table 2*.

Table 1: Measured site characteristics. Peat depth and depth to water table are shown plus or minus one standard deviation of the mean. Depth to water table is shown as depth below the soil surface and was measured via water table wells installed at each research site.

	Site	**Average Peat Depth (cm)**	**Avg. Growing-Season Depth to Water-Table (cm) (May 21 - Oct. 10, 2018)**	**Average LAI by Site**	**Basal Area (m^2 per hectare)**
Cloquet Forestry Center (CFC)	CFC-1	56 ± 6	4.5 ± 5.1	3.565	70
	CFC-2	181 ± 43	4.8 ± 2.0	2.285	80
Hubachek Wilderness Research Center (HWRC)	HWRC-1	221 ± 7	4.9 ± 1.9	1.47	90
	HWRC-2	137 ± 32	1.9 ± 1.9	1.41	160
Marcell Experimental Forest (MEF)	MEF-1	225 ± 9	8.5 ± 3.1	0.635	50
	MEF-2	146 ± 38	4.8 ± 1.7	0.625	90

Table 2: Climate and weather characteristics by site. Measured air temperature values are shown plus or minus one standard deviation of the mean.

Site	30-Year Normal Winter (Dec-Feb) Air Temp (°C)	Avg Measured Air Temp (°C), Dec. 2017 - Feb. 2018	Avg Measured Air Temp (°C), Dec. 2018 - Feb. 2019	30-Year Normal Air Temp Oct-Apr (°C)	Avg Measured Air Temp (°C), Oct. 2017 - Apr. 2018	Avg Measured Air Temp (°C), Oct. 2018 - Apr. 2019	30-Year Normal Snowfall (cm)	Total Snowfall (cm) (2017-2018)	Total Snowfall (cm) (2018-2019)
CFC	-10.6*			-3.8*			146.1*	182.6**	174.5**
CFC-1		-13.2 ± 9.0	-11.3 ± 8.2		-6.9 ± 10.0	-5.2 ± 9.8			
CFC-2		-13.1 ± 9.0	-10.6 ± 8.6		-6.9 ± 9.9	-4.8 ± 9.8			
HWRC	-12.8*			-5.6*			177.8*	233.7***	153.2***
HWRC-1		-13.1 ± 9.1	-11.2 ± 8.5		-6.7 ± 10. 1	-6.8 ± 10.5			
HWRC-2		-13.2 ± 9.0	-13.2 ± 9.0		-6.7 ± 10.1	-9.3 ± 10.5			
MEF	-12.2*			-4.8*			152.4*	130.3***	185.7***
MEF-1		-13.2 ± 9.0	-12.5 ± 8.5		-6.7 ± 10.1	-9.1 ± 10.3			
MEF-2		-13.1 ± 9.1	-12.0 ± 9.1		-6.7 ± 10.1	-6.9 ± 10.7			

*Data obtained via MN State Climatology Office 1981-2010 30-Year Normals Map Portal, last updated February 2017. Data source for the portal is PRISM Climate Group, Oregon State University.

**Data retrieved via XM-ACIS database. All data meets the standards of the National Oceanic and Atmospheric Administration (NOAA).

***Data retrieved from NOAA. Nearest snowfall reporting station to MEF is located just north of Grand Rapids, MN.

Experimental Design

This study was conducted over the course of two winter seasons, beginning in the autumn of 2017 and ending in the spring of 2019. A paired-plot experimental design was utilized for this study, with two sites at each of the three study locations. Each research site (replication) was composed of two plots: a snow removal (treatment) plot and an ambient snow cover (control) plot (*Figure 2*). Each plot measured 4x4 meters with approximately one meter spacing between plots. The plots were constructed in east/west orientation and were randomized as to which plot received snow removal and which was left as a control at each site.

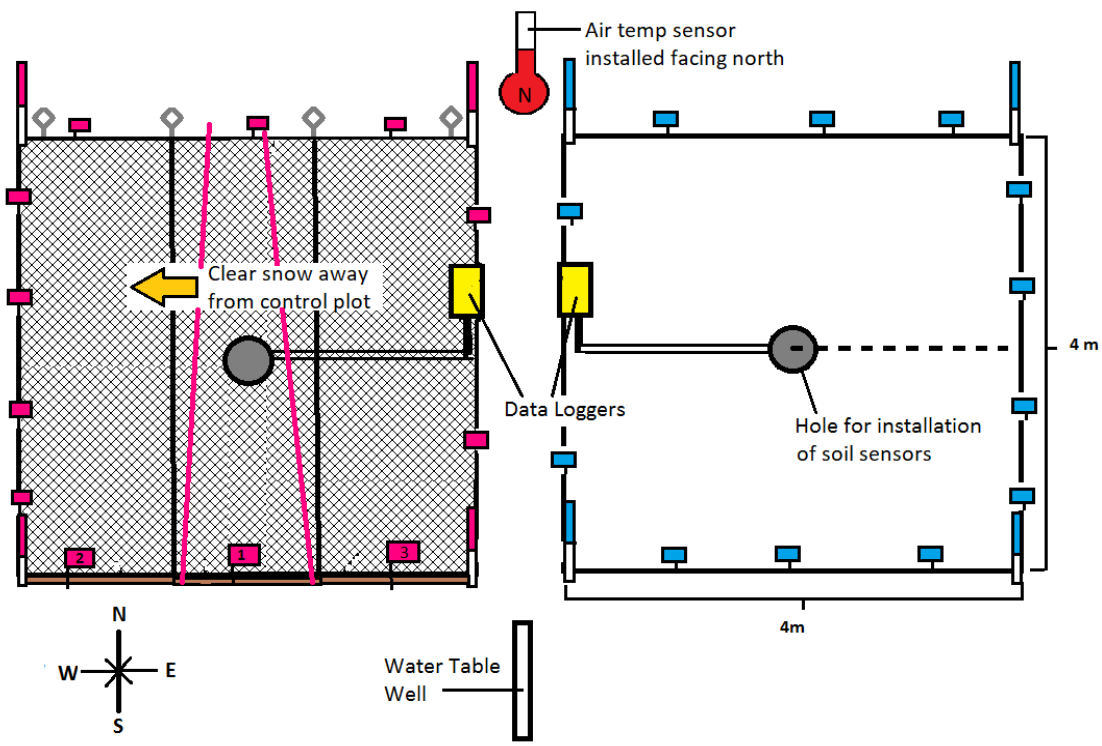


Figure 2: Schematic of the paired-plot experimental design. Plots were constructed in east-west orientation and were randomized as to which plot received snow removal treatment at each site.

Equipment & Installation

Measurements recorded at each site included soil temperature and moisture, frost depth, air temperature, and water table level fluctuations relative to the ground surface. In addition, peat depth, leaf area index and basal area measurements were conducted at each site.

Frost development in peatland soils was analyzed using soil temperature as a proxy for frost, as well as through direct measurements of soil frost thickness. Soil temperature was measured via Decagon 5TM temperature/moisture sensors (+/- 1.0°C, +/- 0.03 m^3/m^3; METER Group, Pullman WA) installed at depths 5, 10, 15, 20, 40, and 60 cm in each ambient snow cover (control) plot and at 5, 10, 15, and 20 cm in each snow removal plot. The soil temperature at depths 40 and 60 cm of the snow removal plots was measured via iButton sensors (+/- 0.5°C; Maxim Integrated Products, Inc., Sunnyvale CA) housed in water-tight casings. Measurement interval for the 5TM sensors was 15 minutes, while the iButton sensors recorded temperature at 180 minutes intervals, due to constraints in sensor memory.

Shallow soil pits were excavated near the center of each study plot to allow for sensor installation and were backfilled following installation (*Figure 2*). The soil depths for installation were measured from the peat surface, which was identified via visual inspection of the soil profile beneath the living sphagnum layer, and sensors were fully inserted horizontally into the pit wall to limit artifacts associated with backfilling. Decagon EM50G data loggers (METER Group, Pullman WA) were used to log soil temperature and moisture data from the 5TM sensors. The data loggers were housed in foam-lined Pelican-style cases to insulate them from adverse winter weather conditions.

This was found to be effective at expanding the operating conditions for the EM50G data loggers to conditions with air temperatures below -30°C.

Air temperature was measured at each site with either HOBO temperature and relative humidity sensors (+/- 0.21°C, +/- 2.5%; model U23 Pro v2, Onset Computer Corporation, Bourne MA) or Thermochron® iButton sensors (+/- 0.5°C; model DS1921G, Maxim Integrated Products, Inc., Sunnyvale CA). The air temperatures sensors were all installed at approximately one meter from ground level on the north side of the study plots (*Figure 2*). The sensors were installed north-facing to avoid direct sunlight.

A water table well was installed at each site to monitor ground water levels during the growing season (*Figure 2*). The wells were installed within two to three meters to the north or south of the plots. Barometric pressure was also measured at each location to account for atmospheric pressure on water level readings. Both barometric pressure and water table level were recorded at 15-minute intervals via HOBO model U20L loggers (Onset Computer Corporation, Bourne MA).

Additional site characteristics, including peat depth, leaf area index (LAI), and basal area, were measured once during the course of the study. Peat depth was measured using a manual depth probe during the summer of 2018, as was LAI. LAI was calculated by use of Accupar LP-80 Ceptometer (METER Group, Pullman WA), and measurements were taken during mid- July, 2018. Basal area measurements were conducted during the spring of 2019 via a factor 10 wedge prism.

Snow Removal

To remove snow cover from the sensitive organic soils that compose peatlands, a system was needed that would avoid damage to the soil and sphagnum moss cover that could occur through conventional shoveling techniques. To address this issue, lengths of aluminum window screening were draped over the snow removal plots to operate as a snow removal mechanism and as a barrier to capture snowfall prior to it reaching the ground (*Figure 2* and *Figure 3*). The screening used was standard aluminum window screen, with a charcoal grey coating to most closely mimic the albedo of surface cover at the sites (Phifer Incorporated, Tuscaloosa AL). The window screen was selected as a tool for snow removal because it was able to intercept most snowfall without shading the plot or inhibiting infiltration or gas exchange. The ambient snow cover (control) plots were not covered with screening, and a graduated dowel for measuring snow depth to the nearest centimeter was installed near the center of the plot on the flattest available ground surface, given the microtopography of hummocks and hollows.

Snow was removed from the treatment plots within 24 hours or one business day following a snowfall event of 5 cm or more. If no snowfall event of 5 cm or greater occurred in a week, the plots were checked once per week, snow depth measured, and removal plots cleared of incidental snow as necessary.

Several techniques were employed to remove snow cover from the snow removal plots. Often, the technique utilized depended upon the depth and moisture content of the snowfall. For light, dry snowfall and clearing of small amounts of snow, the screening system on the removal plots were lifted and the snow shifted off the plot and away from the control plot. Following heavier snowfall events, or if the screens became frozen to the ground surface during freeze-thaw cycles, the plots were cleared with a shovel via conventional shoveling of the snow off the screen, or via leaf blower, with the snow being blown to the north and/or away from the control plots.

a)

b)

Figure 3: Images depicting the experimental design a) immediately following installation and b) following a snowfall event. The screening system used for snow removal can be seen in both images. This system was found to be effective at intercepting most snowfall and in acting as a barrier off which snow could be more easily removed without damaging the soil and surrounding ecosystem.

Frost Measurement

In addition to collecting soil temperature, the depth of soil frost was also recorded in plots at each site to validate the use of soil temperature as a proxy for soil frost and for additional analyses. The protocol utilized in this study for measuring the frost depth was previously developed at MEF and was implemented without major modification (USDA Forest Service, 2007). A standard drill or hammer drill with a masonry drill bit sized approximately 0.5” x 36” was used to drill through the frost layer, noting the depth (to the nearest inch) at which the bit broke through the concrete frost layer in the soil. In plots with snow cover, the depth the bit could be inserted into the snowpack before hitting frost was recorded, and it was assumed that frost development began at the soil surface in these cases, due to the inability to see the ground cover under the snow.

Soil frost thickness was measured a minimum of once per week, beginning in late January of winter 2017-2018, and throughout the winter of 2018-2019. Frost measurements were taken at both plots at each site, with one measurement in each snow removal plot and one in each ambient snow cover plot. The frost measurements were conducted outside the central 1 m^2 of the plot center to avoid any potential damage to the buried sensors or cables and to limit plot disturbance.

Data Analyses

Statistical analyses were completed using R statistical software (R Core Team 2018) and Microsoft Excel. Soil and air temperature data were distilled to daily and weekly averages for ease of data processing. To determine whether soil temperature is an appropriate proxy for soil frost development, soil temperature and frost measurements were compared both using presence-absence of frost and interpolated frost depth from soil temperature.

Treatment effects on soil temperature were assessed with mixed effects model analysis. The R package ‘nlme’ was utilized to conduct a mixed effects model analysis with repeated measures, with site as a random variable, and treatment, week, and sensor depth modeled as fixed effects (Pinheiro et al., 2017). Correlation of data by time and sensor depth within plot were accounted for in the model with repeated measures analysis by using a ‘corAR1’ function (Pinheiro et al., 2017). To calculate the appropriate covariance matrices for this analysis, the weekly-averaged soil temperature data was divided into subsets of discreet time periods, summarized in *Table 3*. For the purposes of this study, the data from the winter periods was primarily used for analysis. When significant treatment effects were found ($p < 0.05$), least-squared means analyses was used with Tukey adjustment in the ‘lsmeans’ package (Lenth, 2016) to identify weeks and depths where significant differences existed between treatment and control averages across all sites.

Linear regression was used to assess relationships between frost depth and both cumulative freezing degree days (FDDs) and cumulative freezing temperatures during the 2018-2019 winter season both across all sites and at the individual site level. Cumulative FDDs were calculated as the running total of days in which average air temperature was equal to or less than 0°C during the winter of 2018-2019. Cumulative freezing temperatures were the sum of daily average temperatures that were equal to or less than 0°C during the winter of 2018-2019. This regression analysis was conducted 1) across all sites to assess broad treatment effects, and 2) for each individual site to determine if

Table 3: Time periods used for mixed effect model.

		Date Range
Winter 2017 – 2018	Early Winter	10/21/2017 – 12/16/2017
	Mid-Winter	12/23/2017 – 02/17/2018
	Late Winter	02/24/2018 – 04/21/2018
Non-Winter	Spring	04/28/2018 – 06/23/2018
	Summer	6/30/2018 - 8/18/2018
	Autumn	8/25/2018 - 10/13/2018
Winter 2018 – 2019	Early Winter	10/20/2018 – 12/15/2018
	Mid-Winter	12/22/2018 – 02/16/2019
	Late Winter	02/23/2019 – 04/20/2019

site-specific differences existed. In this latter instance, analysis of covariance (ANCOVA) was used to test alternative models allowing for 1) different intercepts and slopes among sites 2) different intercepts among sites, and 3) no difference in slopes or intercepts among sites. Information criteria (AIC and BIC) were used to identify the best of these alternative models.

To investigate the relationship between soil temperature at each sensor depth and how this relationship changed over time, least-squared weekly mean soil temperatures from the mixed effect model (i.e., across all sites) were grouped by treatment using the ‘dplyr’ package (Wickham et al., 2019), then regressed by soil sensor depth and week within each discreet winter time period (*Table 3*). T-tests were conducted to compare the regression coefficients (intercept and slope coefficient) between treatments to determine how the relationship between temperature and depth changed over time between treatments.

Results

The winters of the study (defined as Oct. 2017 – Apr. 2018 and Oct. 2018 – Apr. 2019), were generally colder than average (Minnesota State Climatology Office, 2019). These colder temperatures could be attributed to colder than average shoulder seasons (Oct. – Nov. and Mar. – Apr.), rather than exceptionally cold winter months (Dec. – Feb.). During both winters, air temperature tended to be fairly close to the 30-year Normal temperature for each site during the months of Dec. – Feb. This indicates that while the core winter months were not much colder than is typical, the colder weather likely began earlier and/or persisted later in the season than normal.

The CFC received more snowfall than average during both winters of the study (182.6 and 174.5 cm compared to the 30-year Normal amount of 140 cm) (Minnesota State Climatology Office, 2019). The Ely area (near HWRC) received more snowfall than average during the winter of 2017-2018, receiving 233.7cm compared to the 30-year Normal amount of 165 cm, but received slightly less snow fall than average during the second winter of the study (153.2 cm) (Minnesota State Climatology Office, 2019). The reverse was true of the Grand Rapids area, slightly south of the MEF, which received slightly less than average snow fall during the first winter of the study (130.3 cm, compared to the 30-year Normal amount of 152 cm), and more snow than average during the winter of 2018-2019 (185.7 cm) (Minnesota State Climatology Office, 2019).

Relationship Between Soil Temperature and Soil Frost

To determine whether soil temperature is an appropriate proxy for soil frost, manual measurements of frost depth were compared to average daily soil temperature readings on days in which frost measurements were conducted. This comparison of frost presence with measured soil temperature indicated that in most cases, our measurements of soil frost were in agreement with soil temperature (i.e., soil temperature was < 0°C when frost was observed or > 0°C when frost was absent) (*Table 4*). In 73.9% of cases on snow removal plots and 75.7% of cases on ambient snow cover (control) plots, measured soil temperature and frost depth were in agreement; these results were categorized as "True Frozen" for cases in which soil temperature was < 0°C and frost was present, and "True Thaw" for cases in which soil temperature was > 0°C and no frost was detected (*Table 4*). Because a clear majority of the frost and temperature measurements agree as to the presence of soil frost, these results indicate that soil temperature does provide an appropriate proxy for soil frost presence. In addition, the prevalence of "False Frozen" cases, in which soil frost was detected but the average daily soil temperature was greater than 0°C, indicates that soil temperature is a conservative estimate of soil frost development. The limited number of instances where soil temperature would indicate frozen soil but no frost was detected ("False Thaw") suggests that there is little risk to over-estimating frost presence when using soil temperature as a proxy.

When accounting for the precision of the temperature sensors (+/- 1°C), the use of soil temperature as a proxy tended to remain conservative as a measure of frost. When adding 1°C to the daily average temperature, "False Frozen" error increased under snow removal conditions, while subtracting 1°C from the daily average temperature resulted in a moderate increase in “False Thaw”, “True Frozen”, and “True Thaw” determinations (*Table 4*).

Table 4: Percentage occurrence in which measured frost depth corresponded to average daily soil temperature at depths 5, 10, 15, 20, 40, and 60 cm. “False Frozen” indicates that soil frost was detected, but average daily soil temperature at the corresponding soil depth was > 0°C. “False Thaw” indicates that no soil frost was detected at a particular depth, but the corresponding soil temperature was ≤ 0°C. “True Frozen” indicates that frost was detected and the soil temperature at the corresponding depth was ≤ 0°C. “True Thaw” indicates that no soil frost was detected at a particular depth, and the corresponding soil temperature was > 0°C. Percentage occurrence of each possible category of frost depth to the average daily temperature +/- 1°C is also shown in order to account for the precision of the temperature sensors.

	Snow Removal			**Ambient Snow Cover**		
	Avg. Daily Soil Temp.	Avg. Daily Soil Temp. +1	Avg. Daily Soil Temp. -1	Avg. Daily Soil Temp.	Avg. Daily Soil Temp. +1	Avg. Daily Soil Temp. -1
False Frozen	26%	55%	7%	24%	29%	<1%
False Thaw	<1%	0%	8%	<1%	0%	20%
True Frozen	49%	29%	78%	5%	0%	28%
True Thaw	25%	16%	7%	71%	71%	52%

In addition to utilizing a comparison of frost depth and soil temperature to validate the use of soil temperature as a proxy for frost presence, linear regression was also used to interpolate expected frost depth from measured soil temperatures (*Figure 4*). For this regression, soil temperature was assumed to have a linear relationship across depth, which allowed for an estimation of the depth at which the soil temperature increased above 0°C, indicating unfrozen soil. These interpolated values were then plotted against measured frost depths. Cases in which soil temperature was greater than 0°C but frost was measured (“False Frozen” error) were removed prior to conducting regression. In addition, outliers from the interpolated data, determined as points which were further than 1.5 * IQR above the third quartile or below the first quartile of a boxplot of the data (where IQR is the inter-quartile range), were removed prior to comparing the interpolated frost values with those measured in the field. A 1:1 relationship would be expected if soil temperature provided exact estimates of soil frost depth. As can be seen in *Figure 4*, the interpolated depths do fall reasonably close to the 1:1 ($y = x$) line but are consistently above the line indicating that measured frost depth tends to be greater than interpolated frost depth based on soil temperature. This reaffirms that soil temperature may be a conservative estimate of soil frost. The best fit line for this

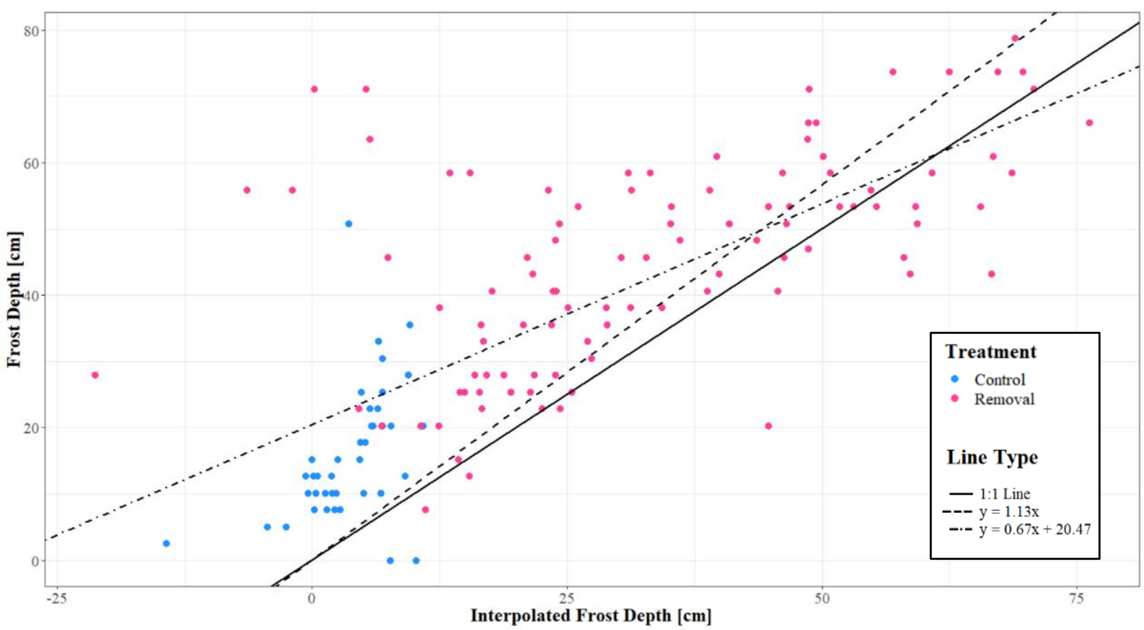
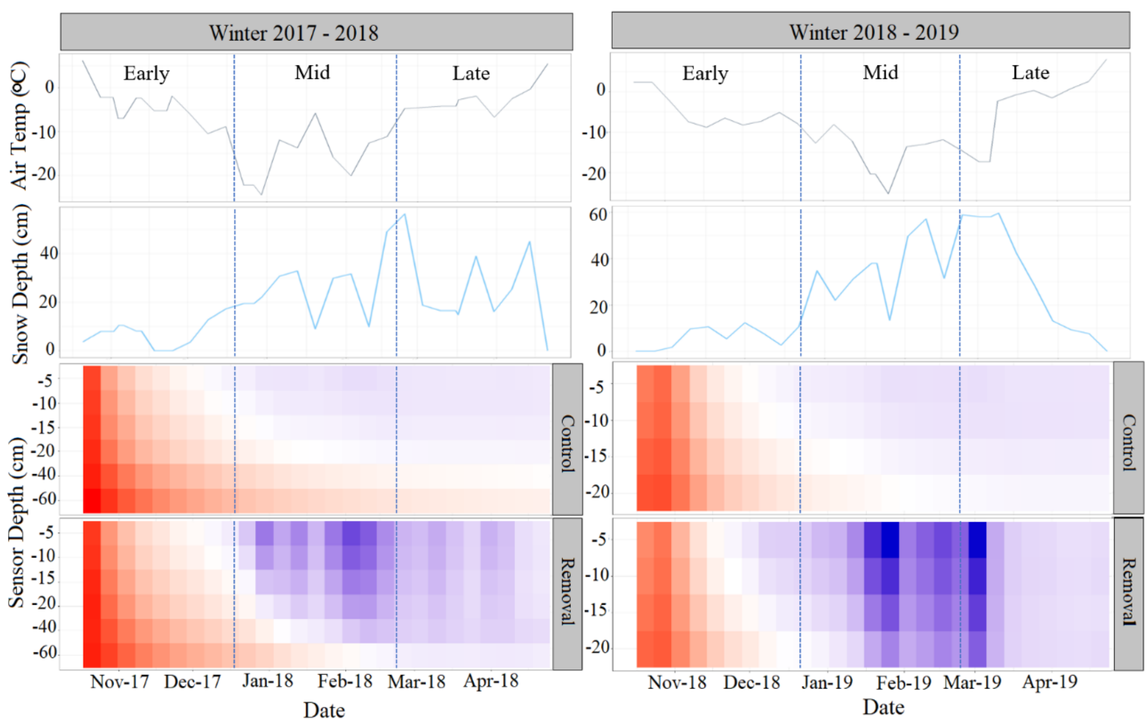


Figure 4: Frost depth interpolated from soil temperature measurements versus measured frost depth. The 1:1 relationship line ($y = x$) is shown as a solid line, while the best-fit linear regression line ($y = 0.67x + 20.47$) for the data is represented by a dot-dashed line and the regression with intercept forced through 0 ($y = 1.13x$) is depicted by a dashed line.

data is $y = 0.67x + 20.47$, with $R^2 = 0.53$. When forcing the intercept through 0 to account for the reality that frost depths cannot occur above soil depths of 0 cm (ground surface), the equation of best fit for the data is $y = 1.13x$ with $R^2 = 0.79$.

Treatment Effects on Soil Temperature

Mixed effect models indicated significant 3-way interactions among treatment, soil depth, and week on soil temperature during the mid- and late-winter time periods in both winters 2017-2018 and 2018-2019 (*Table 5; Table 6*). In general, soil temperatures were significantly colder under snow removal conditions by mid-winter than under ambient snow cover conditions, and remained colder throughout the late winter period with soil temperatures dropping well below 0°C (*Figure 5*). Mean soil temperature in the



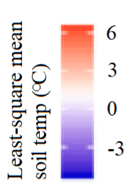


Figure 5: Weekly mean air temperature, snow depth, and soil temperature averaged across all sites by sensor depth for winter 2017-2018 and 2018-2017 as shown by heat graph. Below-freezing temperatures are indicated by blue. Note that during the winter of 2018-2019, only data through soil depths of 20 cm are presented.

ambient treatment was almost always at or above freezing across all sensor depths throughout the study period. During the early winter, soil temperatures were largely similar despite differences in snow cover during the two winters of this study.

In addition to developing colder soils, soil temperatures in snow removal plots tended to closely mirror fluctuations in air temperature during the winter season (*Figure 6; Figure 7; Figure 8*). This relationship is evidenced by the close tracking of soil temperature changes to air temperature changes in the snow removal plots under frozen conditions which are not seen in the ambient snow cover plots (*Figure 7; Figure 8*). The relationship between air temperature and soil temperature is evident during both winters of the study to depths of 20cm and is even apparent during the later mid-winter period of winter 2017-2018 at depths of 40cm or greater. This points to the insulating capacity of snow cover on the ambient snow cover plots that buffers against large shifts in temperature even during periods of extreme cold, while soils with no snow cover can experience relatively rapid and large changes in soil temperature. Because the soils under the snow removal plots experienced temperatures well below 0°C during the winter of 2017-2018 even to depths of 40cm, the soils remained colder in these plots into the summer of 2018 in the upper soil profile (5, 10,15, and 20cm), and into the fall in the deep soil (40 and 60cm) (*Figure 6*). For example, soil temperatures were still significantly colder in the snow removal plots at 40 and 60cm depths for the first two weeks of the autumn period (Aug. 25 – Oct. 13, 2018), but there was no significant treatment effect at any soil depth by the third week of autumn going into the second winter of the study (*Figure 6*).

Table 5: Three-way ANOVA results summary for the soil temperature model showing model coefficient p-values and numerator degrees of freedom for data collected during the winter of 2017-2018.

		Early Winter 10/21/17 – 12/16/17	**Mid-Winter** 12/23/17 – 2/17/18	**Late Winter** 2/24/18 – 4/21/18
Model Term	**Degrees of Freedom**	p-value	p-value	p-value
Treatment	1	0.1215	<0.001	<0.001
Week	8	<0.001	<0.001	0.6704
Sensor Depth	5	<0.001	<0.001	<0.001
Treatment:Week	8	0.4473	<0.001	<0.001
Treatment:Sensor Depth	5	<0.001	<0.001	<0.001
Week:Sensor Depth	40	<0.001	<0.001	<0.001
Treatment:Week:Sensor Depth	40	1.000	<0.001	<0.001

Table 6: Three-way ANOVA results summary for the soil temperature model showing model coefficient p-values and numerator degrees of freedom for data collected during the winter of 2018-2019.

		Early Winter 10/20/18 – 12/15/18	**Mid-Winter** 12/22/18 – 2/16/19	**Late Winter** 2/23/19 – 4/20/19
Model Term	**Degrees of Freedom**	p-value	p-value	p-value
Treatment	1	0.0013	<0.001	<0.001
Week	8	<0.001	<0.001	0.0795
Sensor Depth	3	<0.001	<0.001	<0.001
Treatment:Week	8	0.0009	<0.001	<0.001
Treatment:Sensor Depth	3	0.7678	<0.001	0.0041
Week:Sensor Depth	24	0.0008	<0.001	<0.001
Treatment:Week:Sensor Depth	24	1.000	<0.001	<0.001

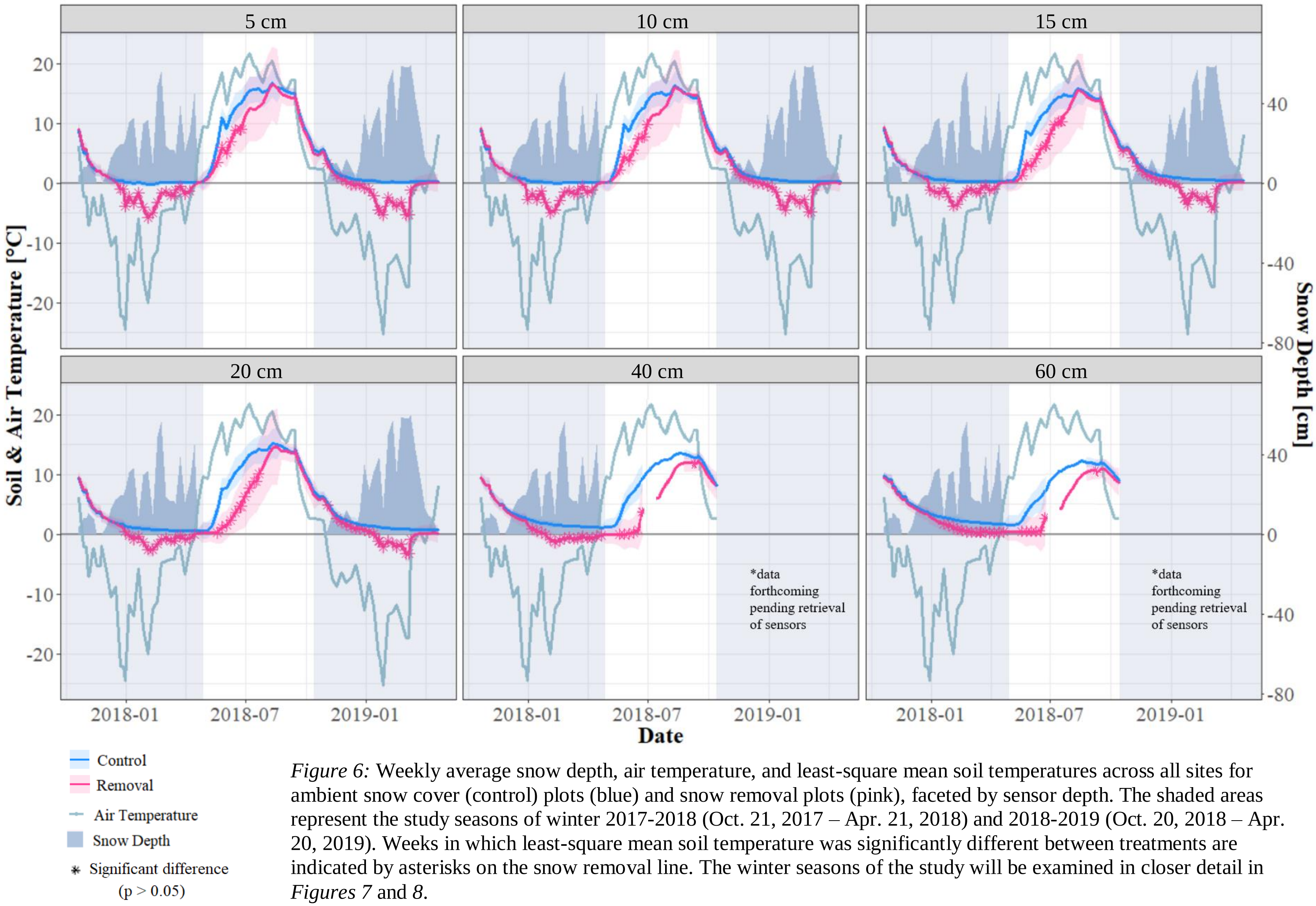


Figure 6: Weekly average snow depth, air temperature, and least-square mean soil temperatures across all sites for ambient snow cover (control) plots (blue) and snow removal plots (pink), faceted by sensor depth. The shaded areas represent the study seasons of winter 2017-2018 (Oct. 21, 2017 – Apr. 21, 2018) and 2018-2019 (Oct. 20, 2018 – Apr. 20, 2019). Weeks in which least-square mean soil temperature was significantly different between treatments are indicated by asterisks on the snow removal line. The winter seasons of the study will be examined in closer detail in *Figures 7* and *8*.

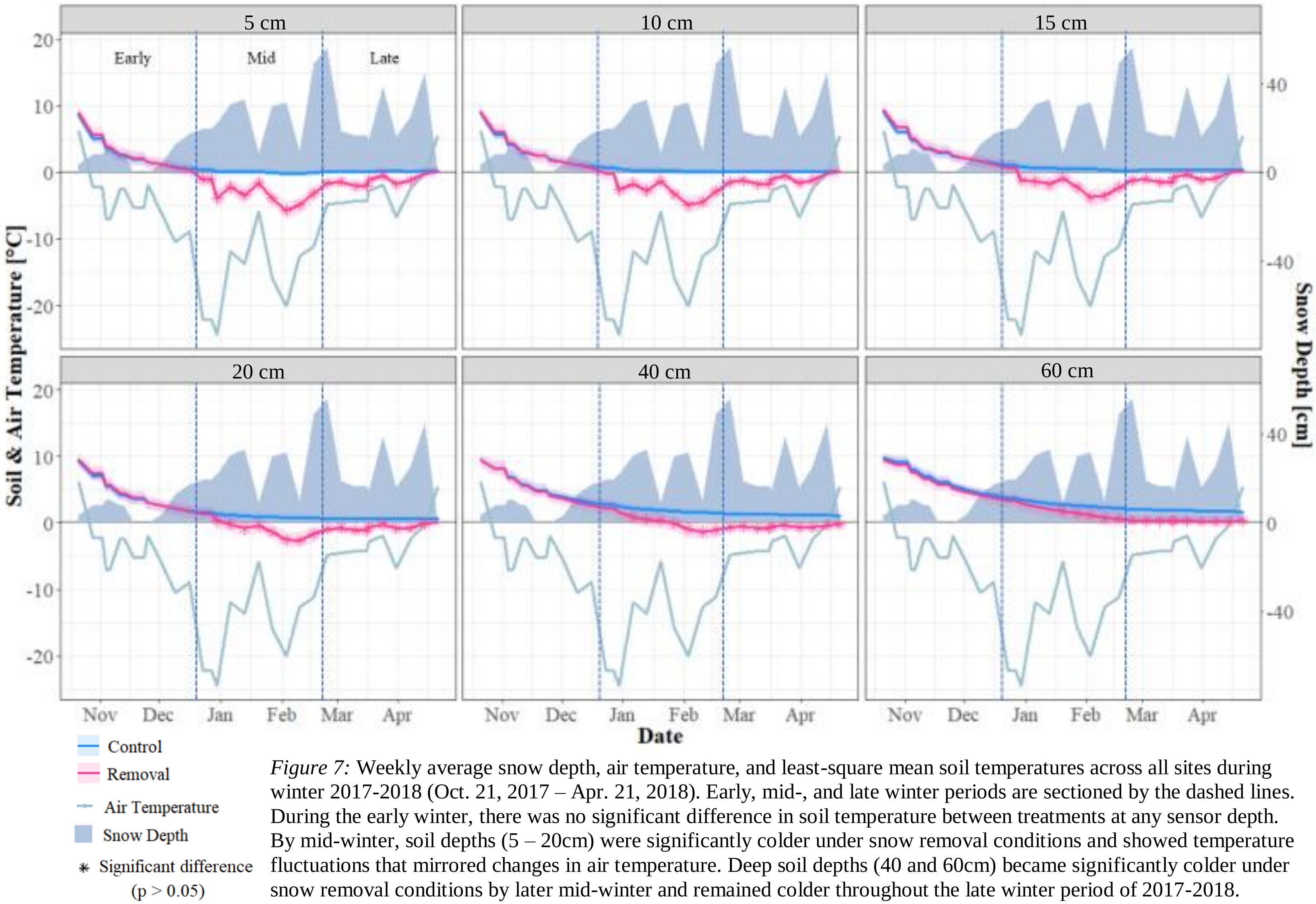


Figure 7: Weekly average snow depth, air temperature, and least-square mean soil temperatures across all sites during winter 2017-2018 (Oct. 21, 2017 – Apr. 21, 2018). Early, mid-, and late winter periods are sectioned by the dashed lines. During the early winter, there was no significant difference in soil temperature between treatments at any sensor depth. By mid-winter, soil depths (5 – 20cm) were significantly colder under snow removal conditions and showed temperature fluctuations that mirrored changes in air temperature. Deep soil depths (40 and 60cm) became significantly colder under snow removal conditions by later mid-winter and remained colder throughout the late winter period of 2017-2018.

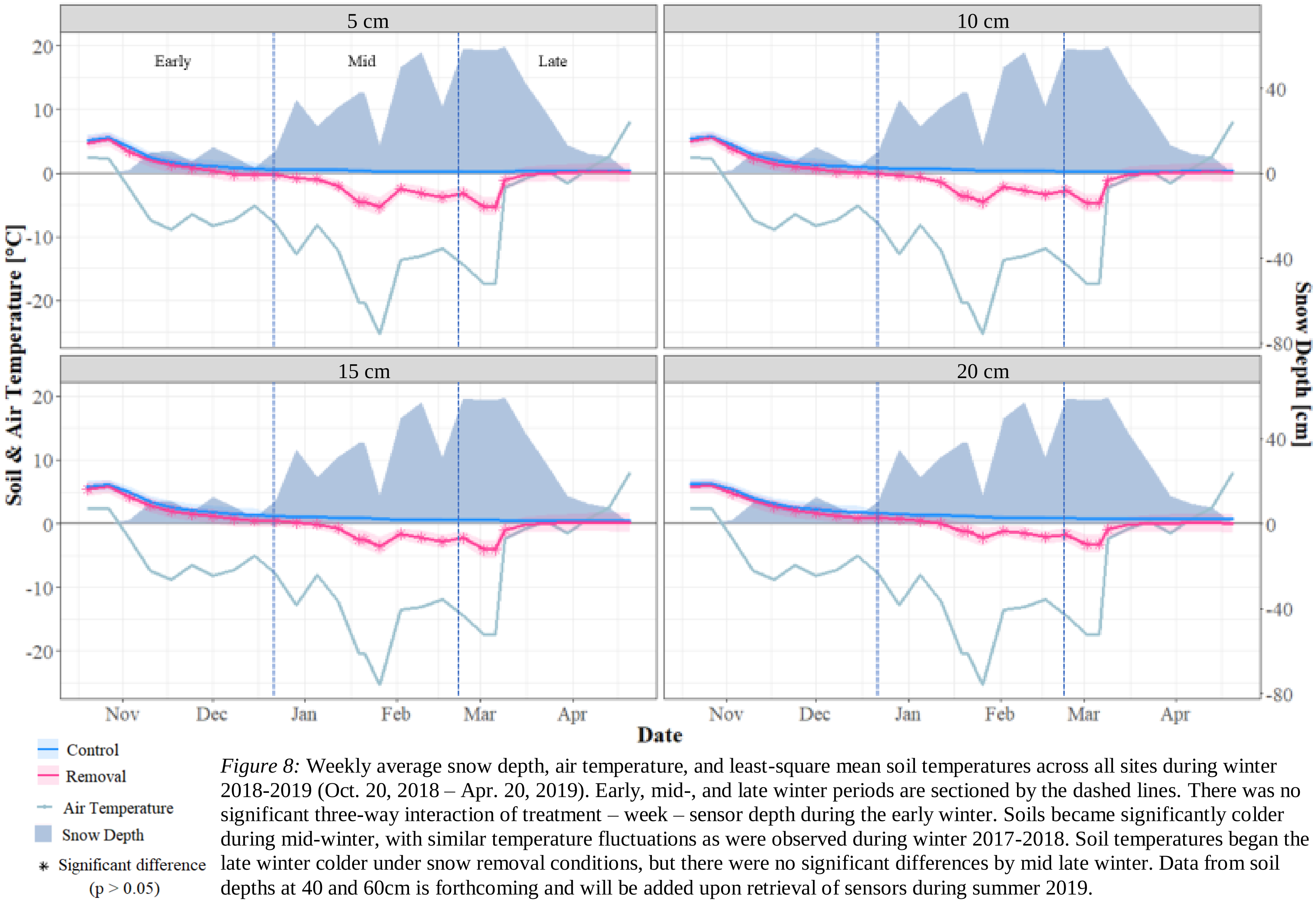


Figure 8: Weekly average snow depth, air temperature, and least-square mean soil temperatures across all sites during winter 2018-2019 (Oct. 20, 2018 – Apr. 20, 2019). Early, mid-, and late winter periods are sectioned by the dashed lines. There was no significant three-way interaction of treatment – week – sensor depth during the early winter. Soils became significantly colder during mid-winter, with similar temperature fluctuations as were observed during winter 2017-2018. Soil temperatures began the late winter colder under snow removal conditions, but there were no significant differences by mid late winter. Data from soil depths at 40 and 60cm is forthcoming and will be added upon retrieval of sensors during summer 2019.

i. Early Winter 2017-2018

There were significant two-way interactions between week – sensor depth and treatment – week during the early winter period of 2017-2018, which may be due to autocorrelation between weeks and soil sensor depths. Pairwise comparison of these interactions produced the following results: (1) for the week – sensor depth interaction, soil temperatures at each respective depth were significantly different between consecutive weeks for the first three weeks of the period at depths 5, 10, 15, 20, and 40cm. At 60cm depth, temperature was significantly different only between the second and third week of the period; (2) for the treatment – sensor depth interaction, soil temperatures were significantly different between depths for all sensors under both removal and ambient snow cover conditions. The average difference in mean soil temperature between consecutive sensor depths (every 5cm) in the upper 20cm was approximately 0.5°C for both removal and ambient condition plots and was 1.1°C and 0.9°C, respectively, for ambient snow cover and snow removal plots at depths 20-60cm (sensors every 20cm).

ii. Mid-Winter 2017-2018

For mid-winter 2017-2018, there was a significant three-way interaction between treatment – week – sensor depth. Pairwise comparison found a significant ($p < 0.05$) effect of treatment during the first week of the mid-winter period at soil sensors depths of 5cm, during the second week of the period for depths 10, 15, and 20cm, during the third week at depths of 40cm, and during the fifth week of the period at depths of 60cm. The differences between treatments remained significant at all depths through the remainder of the mid-winter 2017-2018 period. The average difference in soil temperature between treatments across all depths and weeks was -2.2°C, with larger mean differences in the upper soil profile (-3.3°C at 5cm, -2.9°C at 10cm, -2.4°C at 15cm) than the deeper soil (-1.9°C at 20cm, -1.8°C at 40cm, -1.0°C at 60cm).

iii. Late Winter 2017-2018

There was also a significant three-way interaction between treatment – week – sensor depth during the late winter period of 2017-2018. Pairwise comparison indicated that there was a significant ($p < 0.05$) effect of treatment at all soil depths throughout the first seven weeks of the late winter period. There was no significant difference in soil temperature at sensor depths 5, 10, and 15cm by the eighth week of the period, and no significant difference at 20cm by the ninth week. Soil temperatures remained significantly different between treatments for the entire late winter period at depths of 40 and 60cm. The mean difference in soil temperature between treatments during the late winter period across all depths and weeks was -1.3°C, and the average difference generally increased with soil depth, indicating that shallow soils tended to warm faster during this period than did deep soils.

iv. Non-Winter

During the non-winter periods of the study (Spring, Summer, and Autumn, *Table 3*), there were some significant differences between treatments. During the spring, there were significant two-way interactions of week – sensor depth and treatment – week, but no three-way interaction of treatment – sensor depth – week. From *Figure 6*, it is clear that although temperatures were not significantly different between treatments by the end of the late winter period for 2017-2018, during the spring, temperatures tended to once again trend colder in the snow removal plot, even as air temperatures rose. During the summer and autumn periods, there was a significant three-way interaction between treatment – sensor depth – week. During the summer, soil temperature was significantly colder in the snow removal plots at depths of 10, 15, and 20cm for at least one week during the period. There was not sufficient data from this period to determine if temperatures at 40 and 60cm depths were significantly different between treatments. However, during the autumn period, we did find significantly colder soils at 40 and 60cm for the first two weeks of this period, while temperatures in the upper soil profile were not significantly different. See *Appendix A* for three-way ANOVA results for the non-winter periods.

v. Early Winter 2018-2019

Similar to the early winter of 2017-2018, there were significant two-way interactions of week – sensor depth and treatment – week. Pairwise comparison of these interactions indicated there were some significant ($p < 0.05$) consecutive week-to-week differences in soil temperature at each depth during the early winter of 2018-2019. Pairwise comparison of the week – sensor depth interaction showed that soil temperatures were significantly different from week-to-week during the first three or four weeks of the period across all depths but were not significantly different between the later weeks of the period. The comparison of the treatment – sensor depth interaction showed that, like the early winter 2017-2018 period, the soil temperature was significantly different between depths in each treatment, with mean difference in soil temperature between depths in the upper soil profile (5 – 20cm) equaling approximately 0.4°C for both snow removal and ambient snow cover sites.

vi. Mid-Winter 2018-2019

There was a significant three-way interaction of treatment – week – sensor depth during the mid-winter period of 2018-2019. Pairwise comparison indicated that soil temperatures were significantly different ($p < 0.05$) between treatments at all sensor depths (5, 10, 15, and 20cm) during all weeks of this period. The mean difference in soil temperature between treatments across all weeks and soil sensor depths was -2.4°C, with differences decreasing with depth in the upper 20cm of the soil profile (-2.9°C at 5cm, -2.6°C at 10cm, -2.3°C at 15cm, and -1.9°C at 20cm).

vii. Late Winter 2018-2019

There was also a significant three-way interaction of treatment – week – sensor depth during the late winter period of 2018-2019. Pairwise comparison found significant ($p < 0.05$) effect of treatment on soil temperature at depths of 5, 10, and 15cm through the third week of this period and at depths of 20cm through the fourth week of the period. There was no significant difference by treatment in soil temperature at any soil depth after the fourth week of the late winter period as temperatures approached 0°C in both the snow removal and ambient snow cover plots. During the end of the late winter period, weekly average air temperature increased from below freezing to 5.5°C and snow depth decreased to 0cm as the final snowfall of the season melted, coinciding with the convergence of soil temperature between treatments. The mean difference in soil temperature between treatments across all depths and weeks during the late winter period was -1.3°C. There was little variation from this mean across depths, although there were large week-to-week variations in the mean difference in soil temperature between treatments, with the first two weeks of the period averaging a difference of -3.9°C between treatments across depths, and the later seven weeks averaging a difference of just -0.6°C between treatments.

Relationship Between Frost Depth and Freezing Degree Days

Based on manual measurements of soil frost, frost was found to develop to significantly greater depths under snow removal conditions as compared to ambient snow cover conditions (*Figure 9*). The maximum extent of frost development during the study period was also much greater under snow removal conditions: 78.7cm as compared to 35.6cm under ambient snow cover. In addition, frost was found to persist much longer into the growing season under snow removal conditions than were observed in ambient snow cover plots. Detectable frost was measured in snow removal plots as late as mid-July 2018, over two months later than frost-out occurred on adjacent ambient plots. The soil frost appeared to thaw primarily from the surface down, leaving frost present in the deeper soil profile under a layer of thawed peat.

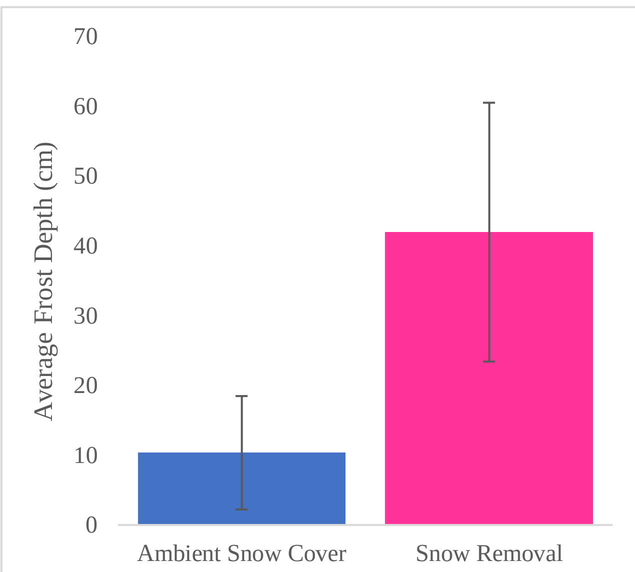


Figure 9: Average soil frost depth across entire study period, as measured via manual frost depth process. Error bars are +/- one standard deviation of the mean. Frost depths under snow removal conditions were found to be significantly deeper than those under ambient snow cover conditions.

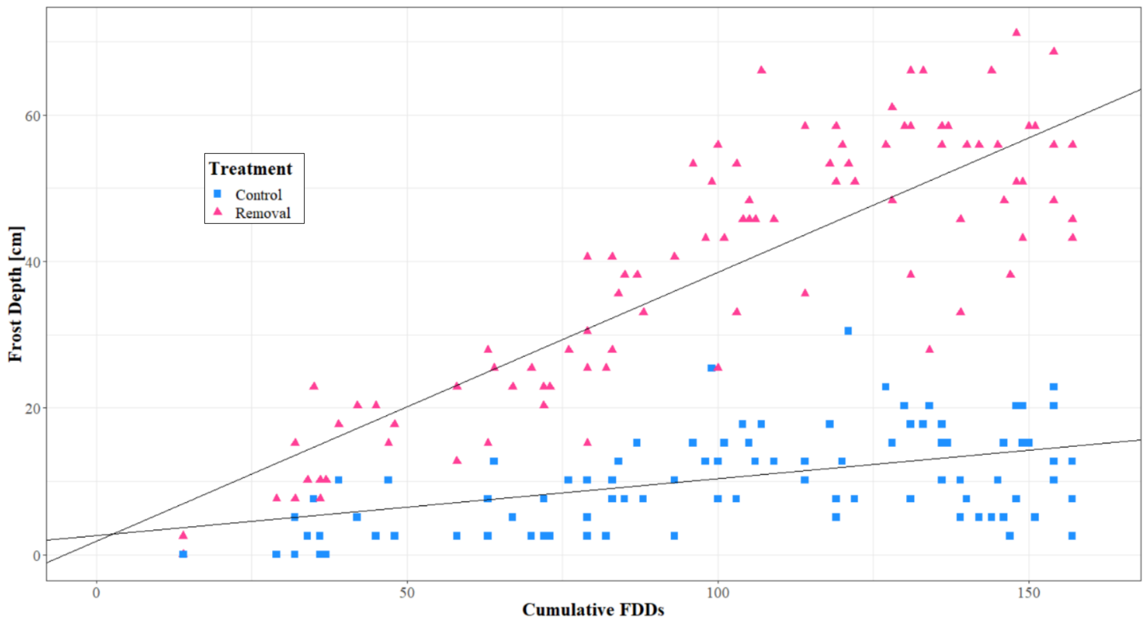


Figure 10: Measured frost depth by cumulative freezing degree days (FDDs). Measurement from snow removal plots are represented by triangles while ambient snow cover (control) plots are squares. Each study site is represented by color. The linear regression lines for snow removal and ambient snow cover plots are also included.

To establish whether a relationship existed between air temperature and soil frost, an analysis comparing freezing degree days (FDDs) to measured frost depth was conducted for winter 2018-2019 data from all sites. FDDs were categorized as any day during the study period in which the average daily air temperature was less than or equal to 0°C. To calculate cumulative FDDs, a running total of FDD-categorized days was generated and was compared to measured frost depths in both snow removal and ambient snow cover plots on the corresponding days. The results of this analysis can be seen in *Figure 10*.

Linear regression was conducted separately for data from snow removal plots and ambient snow cover plots. Both regressions indicated a significant relationship ($p < 0.05$) between cumulative FDDs and frost depth. In snow removal plots, this regression ($y = 0.367x + 1.826$) has an $R^2 = 0.73$, while the regression for the ambient snow cover (control) plots ($y = 0.077x + 2.655$) had an $R^2 = 0.22$. Based on the slope coefficients, it appears that frost develops about 5x faster under snow removal conditions than under ambient snow cover.

Although all sites tended to follow the same general pattern as was evidenced in the global model, visual inspection of the data site-by-site left some question as to whether significant site-specific differences existed in the cumulative FDD-frost depth relationship. In order to determine if there were site-specific differences, a regression line comparison allowing for variable intercepts or slopes among sites was conducted. This comparison found that a model allowing for variable intercepts provided a better fit to the data then the global model (AIC of 1300.2 versus 1318.5 for the snow removal data and AIC of 1038.2 versus 1073.6 for the ambient snow cover data). A pairwise comparison by site of the variable intercept model indicated that for the snow removal plots, site CFC-2 (intercept = -3.39) was significantly different ($p < 0.05$) than sites CFC-1 (intercept = 5.58), HWRC-2 (intercept = 2.79), MEF-1 (intercept = 4.05), and MEF-2 (intercept = 5.77), but was not different from site HWRC-1 (intercept = 0.38). The relationship between cumulative FDDs and frost depth by site on snow removal plots is presented in *Figure 11*. For the ambient snow cover plots, a pairwise comparison by site of the random intercepts model indicated that site MEF-1 (intercept = 5.06) was significantly different ($p < 0.05$) than sites CFC-1 (-0.61) and HWRC-1 (intercept = -0.51), but not different than sites CFC-2 (intercept = 2.63), HWRC-2 (intercept = 2.91), or MEF-2 (intercept = 7.12). Site MEF-2 was also significantly different than sites CFC-1, CFC-2, HWRC-1, and HWRC-2, but not MEF-1. The frost depth – FDD data separated by site for ambient snow cover plots is presented in *Figure 12*.

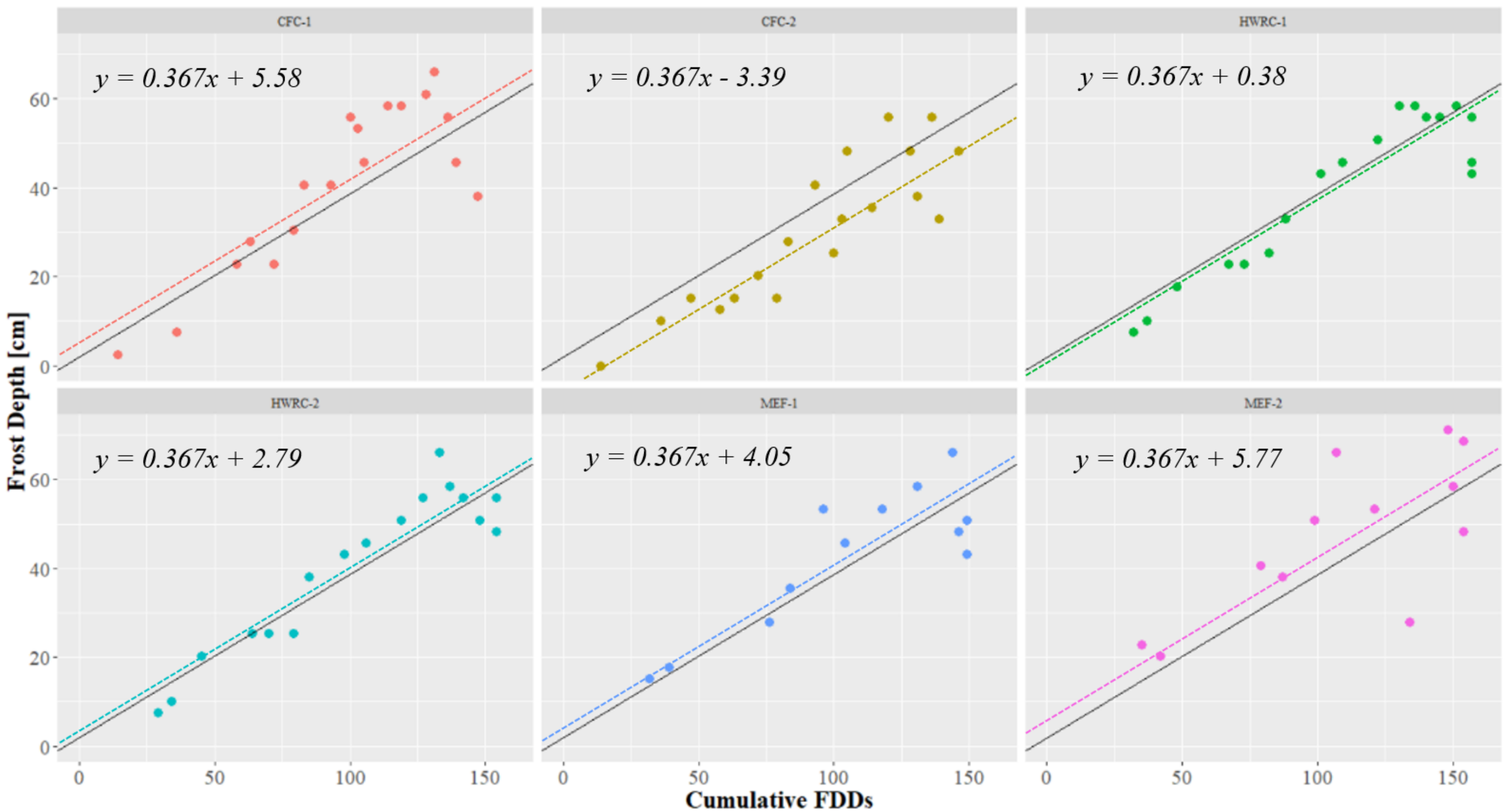


Figure 11: Measured frost depth as a function of cumulative FDDs by site under snow removal conditions. CFC-2 intercept was found to be significantly different (*$p < 0.05$*) from all other site intercepts except HWRC-1. The regression line (black) in this figure is the global regression line for the relationship between cumulative FDDs and frost depth at the snow removal plots.

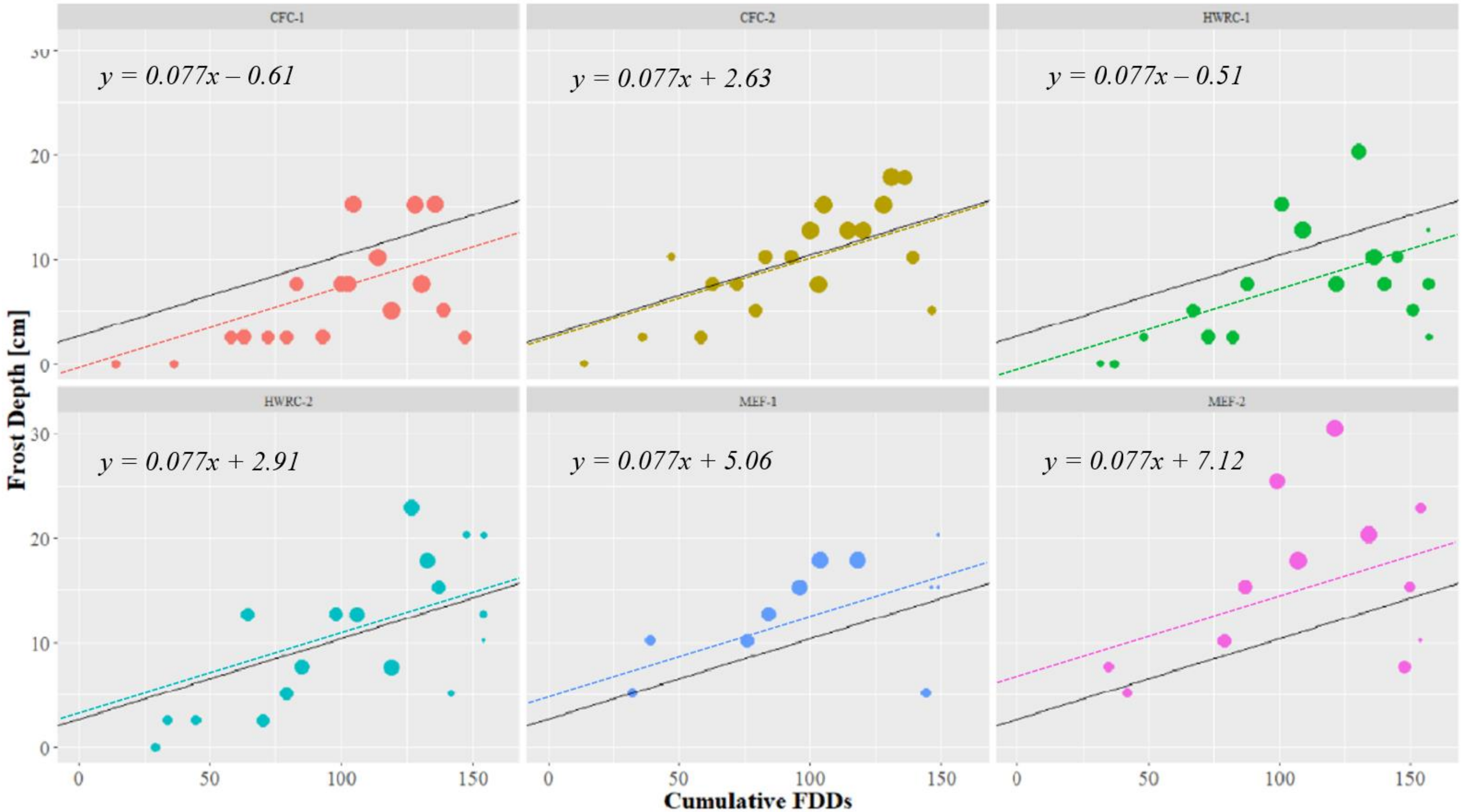


Figure 12: Measured frost depth as a function of cumulative FDDs by site under ambient snow cover conditions. MEF-1 was found to have significantly different intercept than sites CFC-1 and HWRC-1, while MEF-2 was found to have significantly different intercept from all sites except for MEF-1. Snow depth on the ambient snow cover plots is represented by the size of the points, with larger points indicating deeper snow cover. The regression line (black) in this figure is the global regression line for the relationship between cumulative FDDs and frost depth at the ambient snow cover plots.

In addition to comparing measured frost depth to cumulative FDDs, frost depth was also compared to cumulative freezing temperatures, which were calculated by summing all daily average temperatures that were equal to or less than 0°C. This analysis also produced a significant relationship ($p < 0.05$) for both snow removal ($y = -0.031x + 9.35$, $R^2 = 0.78$) and ambient snow cover ($y = -0.007x + 3.68$, $R^2 = 0.27$) treatments (*Appendix B* and *Appendix C*).

Soil Depth Relationship Over Time

To assess how soil temperature varies by depth over time, least square mean soil temperature was grouped by treatment type and regressed by depth and week (*Appendices D, E, F, G, H, and I*). The intercept and slope coefficients of this regression output then underwent a Welch's Two Sample t-test to determine whether significant differences occurred between treatments in how the relationship between soil temperature and soil depth occurred over the course of the winter season.

T-test results indicate there was no significant difference in intercept between treatments during the early winter period in either winter 2017-2018 or winter 2018-2019 (*Table 7*). Intercepts were significantly different ($p < 0.05$) between treatments during the mid- and late winter during both winters of the study. T-test of the slope coefficients found that significant differences existed between treatments during all winter periods investigated.

Plotting the coefficients makes clear the differences between treatments. During both mid- to late winter periods, the intercepts exhibited strong variation under snow removal conditions, while remaining relatively constant under ambient snow cover

Table 7: Welch's Two Sample t-test results for comparing soil temperature/soil depth model coefficients by treatment.

	Early Winter	Mid-Winter	Late Winter	Early Winter	Mid-Winter	Late Winter
		2017-2018			*2018-2019*	
			Treatment ~ y-intercept			
t	-2.09	6.77	9.67	-0.56	5.91	5.117
df	18.2	19.3	29.7	19.2	18.90	20.33
p-value	0.051	< 0.001	< 0.001	0.581	< 0.001	< 0.001
			Treatment ~ slope coefficient			
t	12.87	12.94	12.59	13.05	13.06	12.6
df	17.1	17.1	17.0	17.0	17.3	17.2
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

(control) conditions (*Figure 13; Figure 14; Figure 15; Figure 16*). Slopes were also more variable under snow removal conditions, but under both snow removal and ambient snow cover conditions, slopes tended to get smaller over time after an initial spike in the first couple of weeks of winter (*Figure 13; Figure 14; Figure 15; Figure 16*). These results indicate that as the winter season proceeds, soil temperatures tend to become more uniform across the soil profile under both snow removal and ambient snow cover (control) conditions.

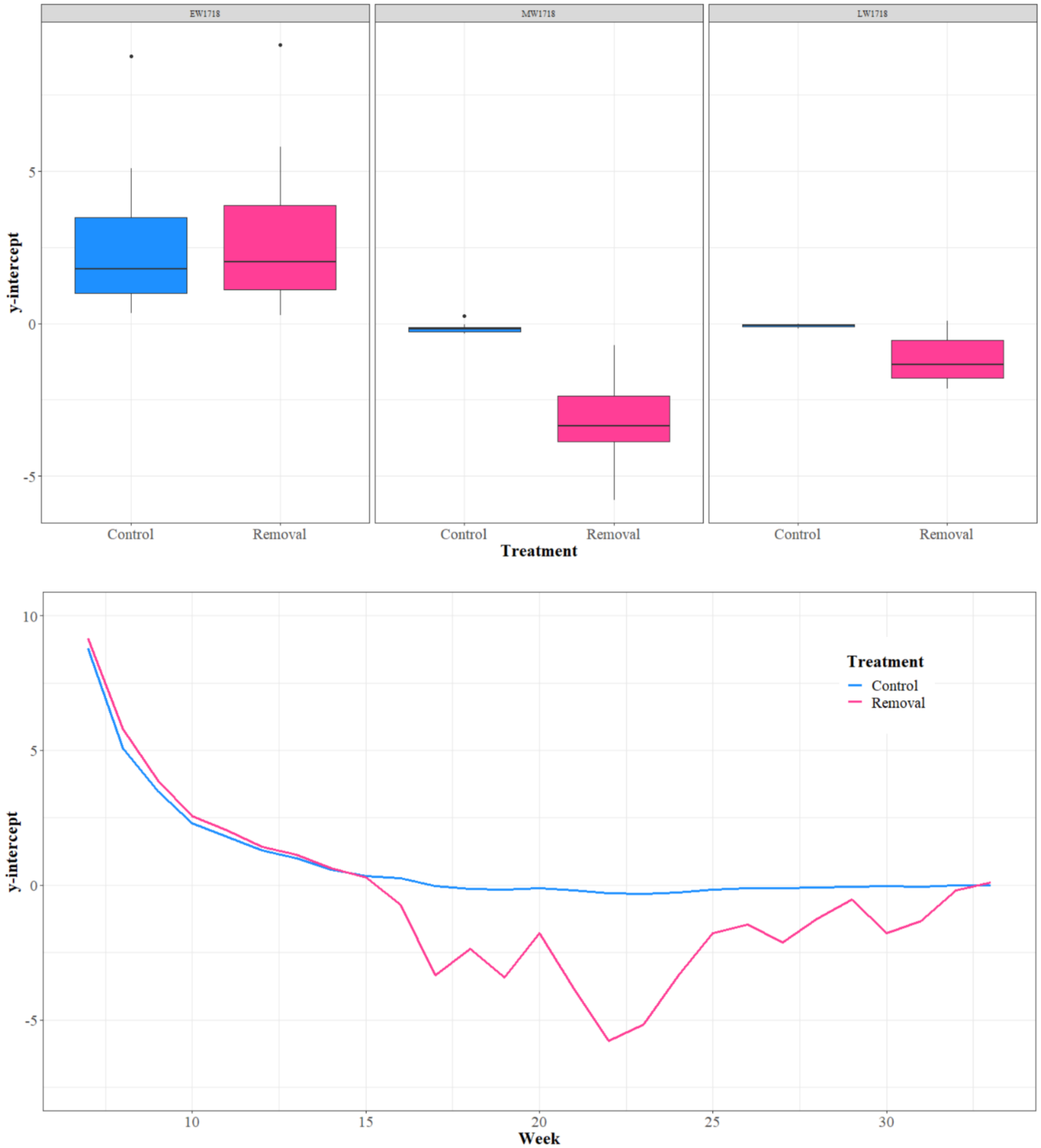


Figure 43: Change in soil temperature/depth model y-intercept over time for the winter of 2017-2018. The upper panel shows a boxplot of the variation in soil temperature/depth model intercepts for each defined period during the winter of 2017-2018. Intercepts are not significantly different during the early winter period (EW1718) but were found to be significantly different during the mid- (MW1718) and late (LW1718) winter periods. Lower panel depicts y-intercept plotted as a function of time. Intercept tended to be more variable under snow removal conditions by the mid-winter period than under ambient snow cover (control) conditions. Y-intercept remained relatively constant at 0°C under control conditions through the mid- and late winter periods.

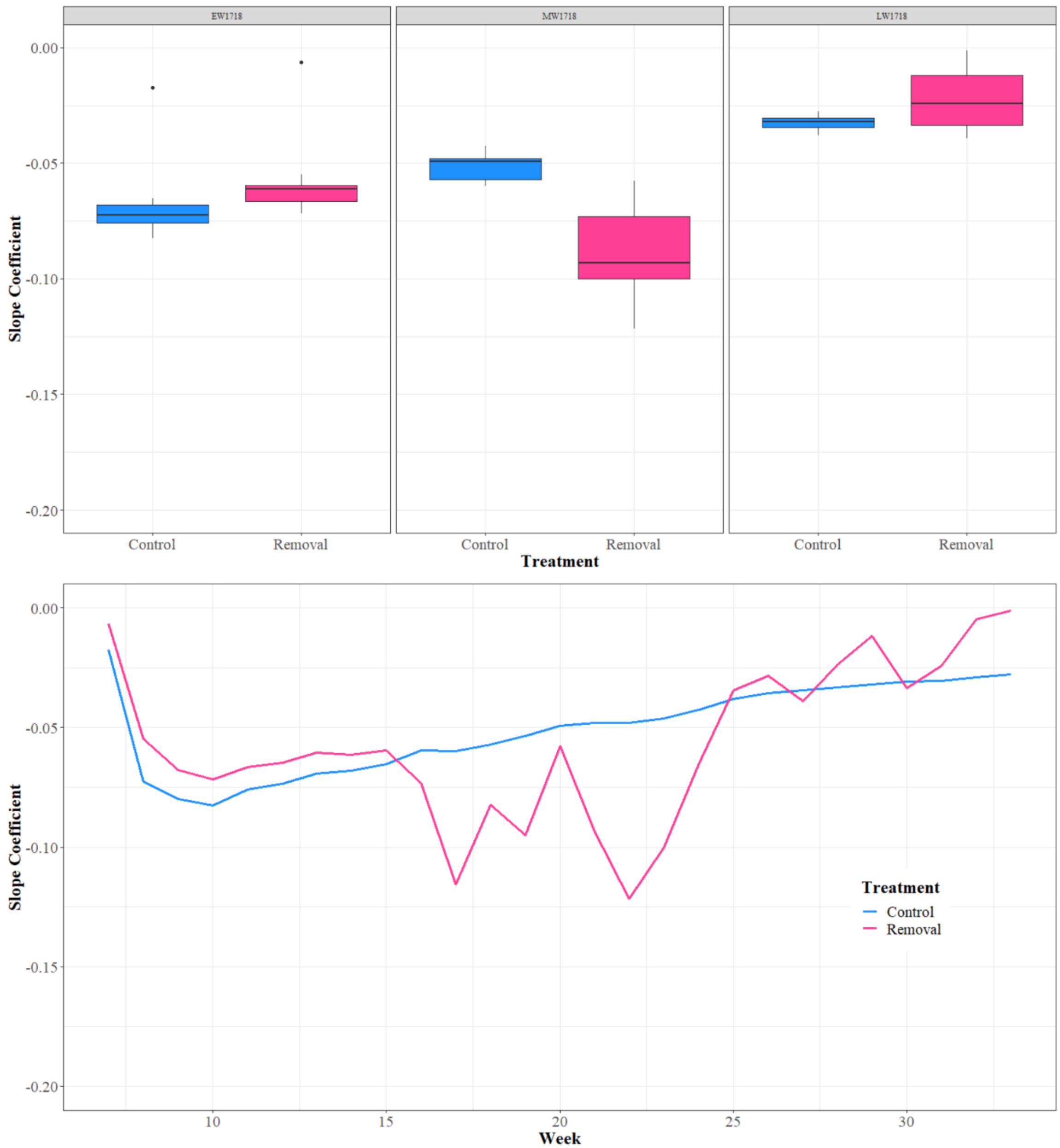


Figure 54: Change in soil temperature/depth model slope coefficients over time for the winter of 2017-2018. Upper panel depicts a boxplot of slope coefficients by winter period, while lower panel depicts slope coefficient plotted again time. Slope coefficient was more variable under snow removal conditions by the mid-winter period than under ambient snow cover (control) conditions. Slope coefficients were found to be significantly different between treatments during all periods, but under both snow removal and control conditions tended to increase towards 0, suggesting more uniform soil temperatures throughout the profile.

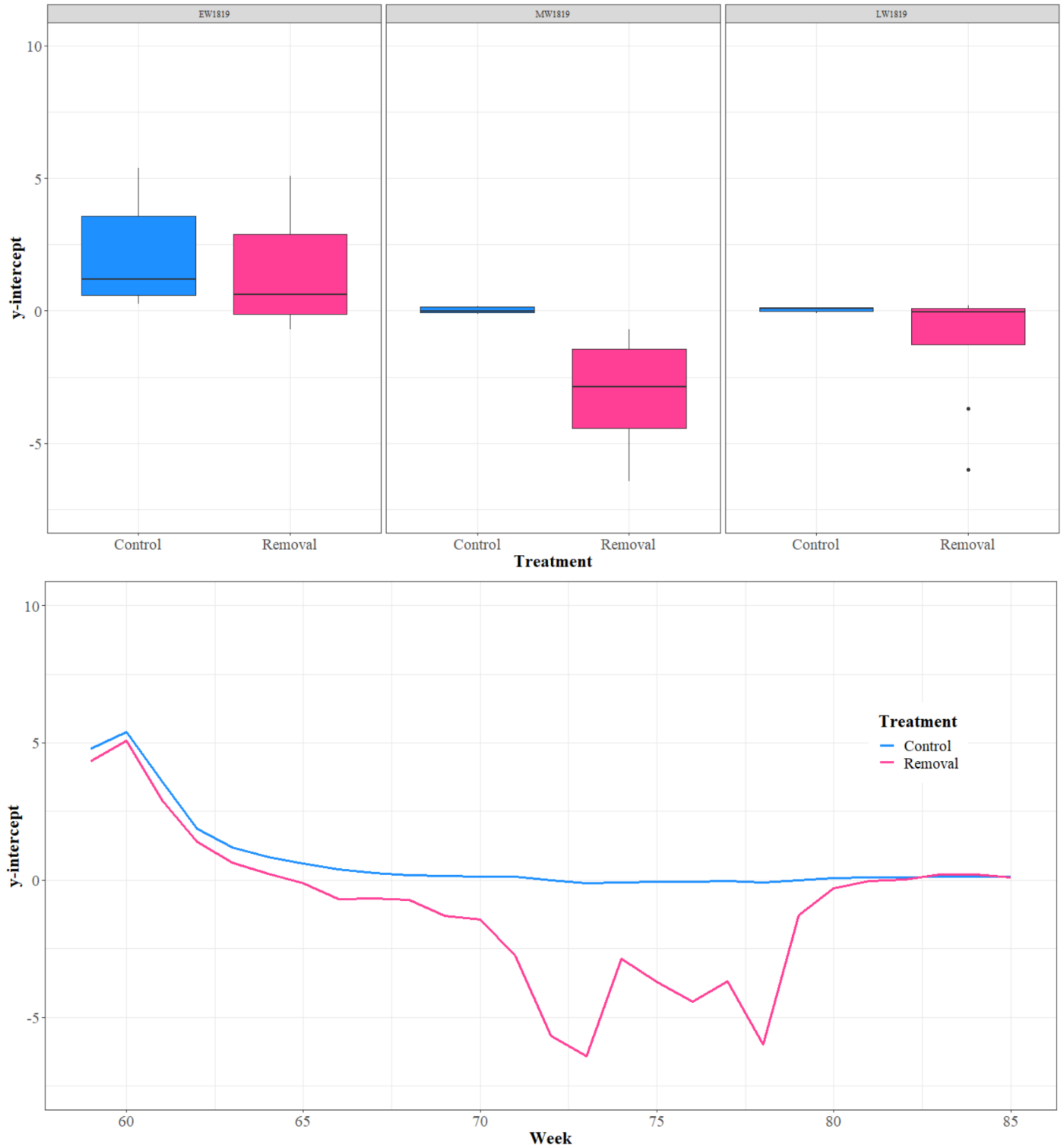


Figure 65: Change in soil temperature/depth model y-intercept over time for the winter of 2018-2019. The upper panel shows a boxplot of the variation in soil temperature/depth model intercepts for each defined period during the winter of 2018-2019. Like the winter of 2017-2018, intercepts were not significantly different during the early winter period (EW1718) but were found to be significantly different during the mid- (MW1718) and late (LW1718) winter periods. Lower panel depicts y-intercept plotted as a function of time.

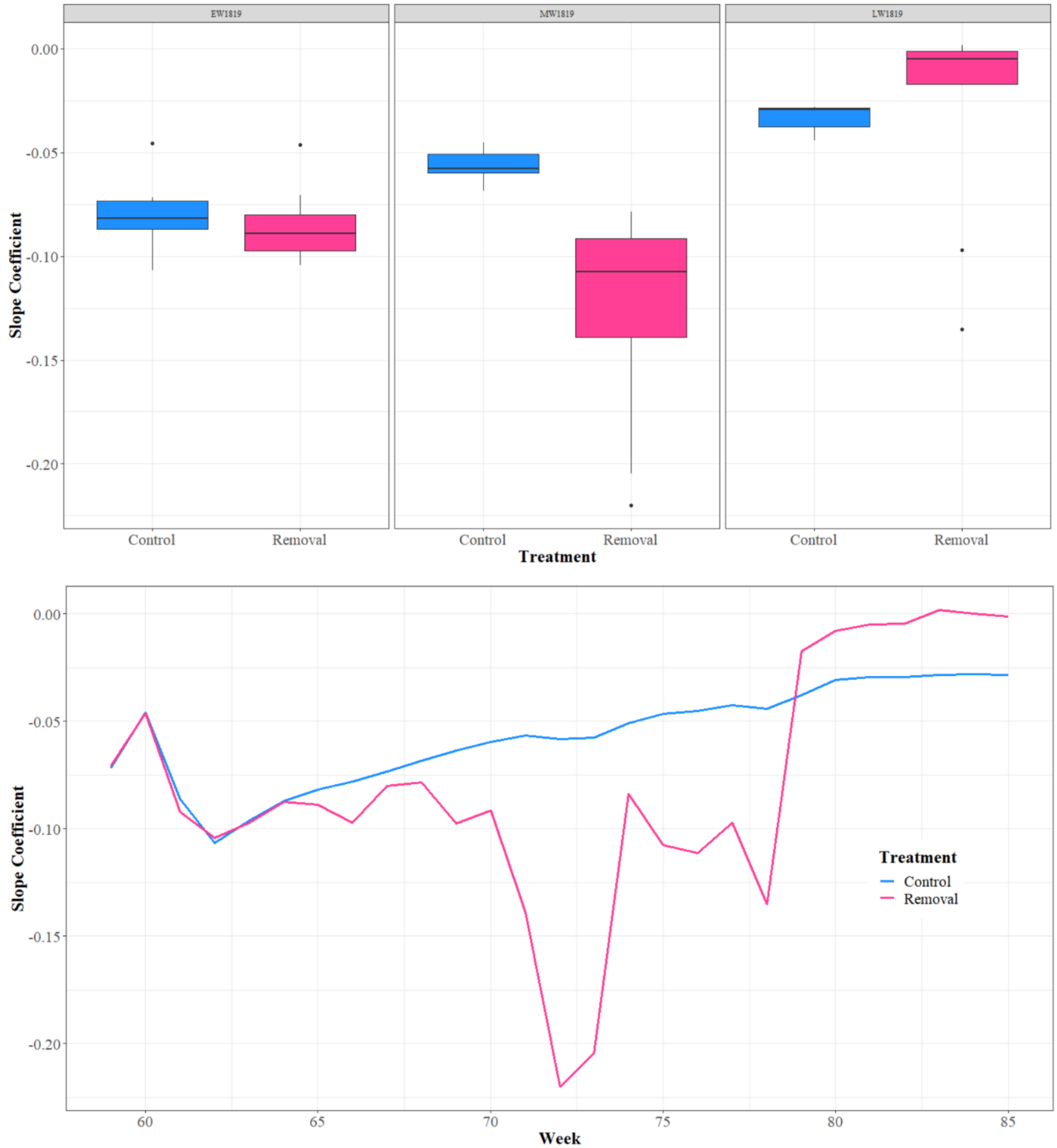


Figure 76: Change in soil temperature/depth model slope coefficients over time for the winter of 2018-2019. Upper panel depicts a boxplot of slope coefficients by winter period, while lower panel depicts slope coefficient plotted again time. Slope coefficients were found to be significantly different between treatments during all periods. The slope coefficients for the ambient snow cover (control) plots trended toward 0 as the winter progressed, while slope coefficients were more variable under snow removal conditions.

Discussion

Alterations to winter processes and characteristics in northern Minnesota are expected as a result of climate change. These changes in winter temperatures and precipitation may uniquely affect forested peatlands because of the influence of temperature and moisture on peatland functional ecology (Gorham, 1991; Hayashi, 2013). This manipulative study shows that a decrease in snow cover may result in significantly colder and more frozen peatland soils during the winter months, with potential impacts on both ecologic and economic benefits. The effect of snow removal treatment varies by soil depth, with wintertime differences at deep soil depths less pronounced and less variable than at shallow depths, and with snow removal treatments remaining colder with persistent frost layers well into the subsequent growing season. Furthermore, soil frost depth increases with increasing cumulative freezing degree days (FDDs) under both snow removal and control conditions, with that increase occurring approximately five times faster under snow removal than ambient (control) conditions.

Soil Temperature and Frost Development

I found the removal of snow cover resulted in colder soils, deeper soil frost, and more persistent soil frost during the seasonal thaw. This corroborates trends that have been found across a range of soil types, including in forested, alpine, and meadow environments, and extends them to forested peatlands (Cleavitt et al., 2008; Decker et al., 2003; Freppaz et al., 2008; Groffman et al., 1999; Groffman et al., 2001; Hardy et al., 2001; Iwata et al., 2010). Several studies also noted increased variability in soil temperature under snow removal conditions, especially at shallow soil depths (Decker et al., 2003; Freppaz et al., 2008; Groffman et al., 1999; Iwata et al., 2010). This is consistent with observations of soil temperature made in this study.

Although the general trends in soil temperature and frost are similar between the present study and previous work, the magnitude of this effect appears to be larger in peatlands than has been observed under mineral soil conditions of previous studies. While previous studies noted that soil temperature was more variable under snow-free conditions at up to 15 cm depth, in this study, we observed fluctuations in soil temperature at depths as deep as 40 cm in response to changes in air temperature (Decker et al., 2003). In addition, the soil temperatures observed in this study in the snow removal plots are consistently colder than those found in previous work. We observed weekly average soil temperatures as low as -7.9°C, with daily averages as low as -10.1°C and individual recorded temperatures as low as -11.3°C in snow removal plots. By contrast, soil temperatures in ambient snow cover (control) plots barely dropped below freezing, with the coldest weekly average soil temperature recorded at -0.5°C, a minimum daily average temperature of -0.65°C, and an individual recorded temperature of -0.7°C. The temperatures recorded in the ambient plots are in-line with those observed by others, reinforcing the importance of snow as an insulator across soil types. Iwata et al. (2010) found soil temperatures as cold as -6°C under snow removal conditions in volcanic ash soils in northern Japan, while soils under undisturbed snow cover were no colder than -2°C. Several other studies conducted in mineral soil environments noted that soil temperatures tended to experience only mild freezing (> -4°C), even under snow removal conditions (Groffman et al., 2001; Hardy et al., 2001; Cleavitt et al., 2008; Freppaz et al., 2008). While Cleavitt et al. (2008) recorded soil temperatures well below 0°C at the soil surface under snow removal conditions, by 10cm soil depth, they did not record any soil temperatures below -4°C, and rarely observed temperatures below -2.5°C. Similarly, Freppaz et al. (2008) recorded minimum soil temperatures of -4.3 and -4.5°C under meadow and forested alpine plots, respectively. By contrast, in this study, individual minimum temperatures lower than -4°C were observed at all sites under snow removal conditions (-8.6°C CFC-1; -3.6°C CFC-2; -4.6°C HWRC-1; -7.9°C HWRC-2; -5.4°C MEF-1; -9.5°C MEF-2).

The measured frost depths in this study also tended to be greater than those recorded in previous work conducted in mineral soil environments. The frost depths measured in a sandy-loam soil at the Hubbard Brook Experimental Forest tended to have large plot-to-plot variation, with major differences by elevation and aspect, with maximum frost depths of around 40-45cm occurring at higher elevation and/or northern aspects, and around 30cm at lower elevation plots under snow removal conditions (Cleavitt et al., 2010; Hardy et al., 2001). The frost depth under control conditions tended to be much less variable based on elevation or aspect, and averaged around 5cm across plots, with deeper frost (10-15cm) under more severe winter conditions (Hardy et al., 2001; Cleavitt et al., 2010). Similarly, Iwata et al. (2010) found soil frost depths of 11cm under control conditions and 43cm under snow removal conditions in volcanic ash soils in Japan. In contrast, the maximum frost depth measured in this study under control conditions was 35.5cm and under snow removal was 78.5cm.

While some factors including variations in climate and methodology between this study and previous work may explain some differences in frost and soil temperature, the magnitude of the treatment effect in this study may be related to the unique properties of peatland soil, such as their waterlogged nature. One of the defining characteristics of peatlands are that they are fully or nearly fully saturated throughout the year. This is reflected by the average water table level observed at the study sites for this project, where the water table was consistently within 5cm of the peat surface, with the exception of site MEF-1, in which the water table was on average 8.5 cm below the ground surface. This high water content likely allowed for the development of concrete frost across the soil profile and to deep soil depths. It has long been recognized that wet peat requires less soil frost thickness than frozen dry peat to bear the same weight (e.g. 35-50 cm frozen depth for dry peat to hold a 10-ton truck, as compared to 25-40 cm frozen depth for wet peat) (Shoop, 1995). This points to the strong, concrete nature of frost layers in frozen peatland soils under saturated conditions, as were observed across the research sites in this study.

In addition to creating a strong concrete frost layer in saturated soils, soil water can act as a strong heat sink – it must absorb a large amount of energy to raise its temperature (Edwards & Cresser, 1992; O'Donnell et al., 2009). To this end, peatland organic soils have low thermodynamic conductivity compared with mineral soil environments (Edwards & Cresser, 1992; O'Donnell et al., 2009). This low thermal conductivity means that temperature changes slowly with depth in saturated peat soils, and helps to explain why the deeper soil profiles in this study remained colder throughout much of the growing season after snow removal, despite warm summertime air temperatures (O'Donnell et al., 2009). The fluctuations in soil temperature observed under snow removal conditions in response to air temperature changes can be attributed to the fact that ice, or in this case, frozen saturated soil, has a higher thermal conductivity than does water (Bonales et al., 2017). The difference in thermal conductivity between water and ice, or soil frost in this case, may also help explain some of the variability observed in the snow removal plots when examining the relationship in soil temperature across depth over time. Compared with ambient snow cover (control) plots, snow removal sites had more variable intercepts and slopes during the mid and late winter periods during both winters of the study, which may largely be attributed to the relatively rapid fluctuations in soil temperature under frozen conditions which are not observed in unfrozen peat soils.

Although much of the previous literature is in agreement with the results observed here, there are some exceptions. Notably, Robroek et al. (2013) found that snow cover manipulation in a mountain peatland bog resulted in warmer soils and earlier thaw under snow removal conditions, while areas where snow cover was added were colder. In that study, the results were largely attributed to the timing of winter snowfall and its importance as an insulator of soil temperature. When air temperatures decrease below freezing before sufficient snowfall is received to insulate the soil, later season snowfall may insulate the colder soils from warming (Robroek et al., 2013). However, when snow cover is established before air temperatures drop precipitously, the snow cover acts to insulate the soil from extreme fluctuations in air temperature, as was observed in this and many previous studies (Groffman et al., 1999; Decker et al., 2003; Iwata et al., 2010; Cleavitt et al., 2008; Freppaz et al., 2008).

While the current study did not qualitatively relate snow depth to soil temperature, previous research has demonstrated the strong insulating capacity of snow cover (Hirota et al., 2006; Seppälä, 1990). Sharratt et al. (1992) pointed to snow depths of

25-35 cm as necessary for soil temperature to reach steady-state, but also found that as little as 15 cm of snow cover may be enough to provide sufficient insulating capacity to maintain steady soils temperatures. In the Lapland of northern Finland, Seppälä (1990) found that when snow depths of less than 30 cm occur, soils become frozen deep enough for the formation of permafrost lenses that persist through the growing season and into the following winter. During the current study, maximum snow depths of approximately 66 cm during the 2017-2018 winter season and 76 cm during the 2018-2019 season were observed on the ambient snow cover plots, well above the 25-30 cm threshold reported in previous work to be necessary to insulate the soil. However, during both winter seasons of the study, snow cover did not accumulate to a depth of greater than 25 cm until the mid-winter period. The lack of insulating snow cover allowed for cooling of the soil at similar rates between treatments during the early winter period. This suggests that had deep snowfall occurred earlier in the season, there may have been even less frost development occurring in the ambient snow cover (control) plots than were observed; conversely, had the study occurred during winters with less snowfall, the magnitude of the difference in soil temperature and frost depth between treatments may have been much less. This inference is supported by the results found in our comparison of frost depth by FDD. While frost depth did increase throughout the 2018-2019 winter in the control plots, the rate of increase was much slower compared to snow removal conditions, suggesting that even as air temperatures dramatically decreased during the mid-winter and into the late winter, the increase in frost was modest by comparison. The insulating capacity of snow cover also explains the lack of variability observed in soil temperature under ambient snow cover conditions in this study. While soil temperatures in the snow removal plots exhibited a large amount of variability, especially during the mid- and late winter periods, by the mid-winter period of both winters, soil temperatures under control conditions were fairly constant at or near 0°C across depths. The variability observed in the snow removal plots was largely driven by rapid changes in soil temperature in the upper soil profile in response to fluctuations in air temperature, which the soils in the control sites did not experience due to snow cover.

As noted in the *Results*, there were some site-to-site variations in frost depth. Under ambient snow cover conditions, site MEF-2 (least-square mean frost depth of 14.2 cm during the winter of 2018-2019) was found to have significantly deeper frost than all other sites in the study, excepting site MEF-1. Greater frost depth at MEF-2 is also demonstrated by the difference in intercept describing the relationship between frost depth and cumulative FDD. The intercept for MEF-2 was greater than that for the global model, indicating that across the time period under investigation, frost depths tended to be deeper at this site than others under ambient snow cover conditions. While this difference may be partially due to climatic or temperature conditions at MEF, it is also likely due to environmental conditions specific to site MEF-2. While most of the research sites for this study were forested ombrotrophic bogs, site MEF-2 is a groundwater fen. A previous study has found that fens tend to have thicker frost layers than bogs, although bogs that are fully saturated may have similar amounts of frost (FitzGibbon, 1981). Additionally, variable thickness of *Sphagnum (sp.)* moss layer is thought to account for much of the variation observed in frost thickness in bogs (FitzGibbon, 1981). This may explain why, under snow removal conditions, site CFC-2 (least-square mean frost depth of 34.0 cm) was found to have significantly less frost than all other sites, except site

HWRC-1, during the winter of 2018-2019. The intercept describing the relationship between frost depth and cumulative FDD at site CFC-2 was less than that for the global model, indicating that frost depths at this site were less than generally observed across the study period. Site CFC-2 had a *Sphagnum* layer that was considerably thicker than many of the other sites, which may have provided extra insulating capacity for the soils at this site, despite the lack of insulating snow cover. In addition, though site CFC-2 had less depth of frost than the other sites in this study, frost was found to be quite persistent into the growing season at CFC-2, with detectable frost measured as late as mid-July after both winter seasons of the study. This again points to the insulating capacity of a thick *Sphagnum* layer, in this case to protect the soil from warming summer temperatures.

Despite these site-specific differences, the response to treatment was relatively consistent across all sites, and the observed results likely provides a good indication of how peatlands across northern Minnesota could respond to decreased snow cover under conditions similar to those observed in this study. The research plots observed in this study were located across the north-eastern portion of Minnesota and represented a gradient of temperate-boreal forest environments, from more temperate forests at CFC to forests dominated by boreal species at MEF and HWRC. The six study sites themselves each consisted of two 4 by 4 m^2 plots located in forested peat bogs and fens. These peatlands differed in size, peat depth, and water table level; they also experienced different amounts of snowfall, changes in air temperature, and spring thaw. However, the consistent response across sites to snow removal – colder soils, increased frost depth, greater persistence of frost – indicate that the results observed here may be generally applicable across peatland ecosystems in northern Minnesota.

Implications for Ecology & Management

Decreased soil temperature and increased soil frost have been associated with an increase in fine root mortality and altered nutrient cycling in several previous studies (Cleavitt et al., 2008; Freppaz et al., 2008; Groffman et al., 1999; Groffman et al., 2001; Tierney et al., 2001). While these studies were conducted in mineral soil forest and alpine environments, the large increases in soil frost depth and the cold, variable soil temperatures observed in the current study may indicate that similar outcomes could occur in peatlands. In addition, the persistent, deep soil frost and colder soils that were observed during the summer of 2018 at all soil depths in the snow removal plots may have further ecological implications that were not observed in previous studies. Previous studies have found that when soil temperatures decrease below -11°C or remain colder for a prolonged period, there is a decrease in bacterial population (Edwards & Cresser, 1992; Robroek et al., 2013). Conditions such as those observed in this study under snow removal conditions, may indicate a loss of bacteria and/or decrease in microbial activity, which may have additional effects on carbon cycling and methane production from peatlands. There is broad consensus that colder temperatures inhibit biologic activity, and studies have found that frozen soil layers play an integral role in whole-ecosystem respiration rates in boreal forests with organic soils (Dunn et al., 2007). Because peatlands store an immense amount of terrestrial carbon, understanding how changing soil frost dynamics may interact with the microbial community and carbon cycling in these systems is critically important (Gorham, 1991; Limpens et al., 2008).

Because this study used relatively small plots within peatland ecosystems, we are unable to quantify how snow removal and subsequent increase in frost may manifest on a larger scale. However, previous research has found that an increase in soil frost is associated with impeded snowmelt infiltration and increased springtime runoff (Hayashi, 2013; Hardy et al., 2001). The increase in runoff could negatively affect the level of the water table, particularly at the beginning of the growing season as air temperatures increase above 4°C and biological activity resumes, but belowground may be considerably colder and remain frozen for much longer (Dunn et al., 2007; Limpens et al., 2008). Because of the relationship between water level/saturation and respiration, seasonal thaw and water table depth have been found to have important control on carbon exchange from peatland ecosystems (Dunn et al., 2007; Limpens et al., 2008). Dunn et al. (2007) found that water table and soil temperature accounted for 60% of the variation in ecosystem respiration observed in a boreal black spruce (*Picea mariana*) forest system, which included some peatlands, with 47% of the total variation attributable solely to soil temperature. This points to the critical relationship between winter processes in peatland soils and summertime fluxes in carbon.

In addition to the potential ecological impacts described above, the findings of this study indicate that decreased snow cover, and lower than average winter air temperature, results in colder soils and increased soil frost depth, potentially increasing accessibility for forest management. Previous work has found that a conservative estimate of peatland soil frost depth of 40-50 cm is necessary to support a 10-ton truck, while most heavy equipment likely can be supported on 30 cm of frozen peat (Shoop, 1995). The regression of frost depth to cumulative FDDs indicates that under snow removal conditions, about 77 FDDs would be necessary for sufficient soil frost formation to occur, which tended to fall around mid-January at all sites. In contrast, even though both winters of this study experienced air temperatures close to average, or even a little colder than average, under ambient snow cover conditions, frost depth of 30 cm or greater was rarely observed at any site, and using the regression generated from observed frost depths and cumulative FDDs, would not produce sufficient frost depth within a reasonable timescale of accumulated FDDs. To combat the insulating capacity of snow cover on frost depth, many foresters currently will use machinery to compact the snow layer, thus reducing the insulating effect. While this process likely produces soil freezing intermediate to the observed depths in this study, future study would be needed to determine exactly how much compaction of the snow is needed to increase frost depths.

In 2014, over 278,000 cords of spruce-fir forest were harvested in Minnesota, and the state has the stock and capacity to allow for harvest of up to 705,500 cords per year (Division of Forestry, 2019). One reason for the difference in cordage harvested versus available cordage may be poor accessibility to some spruce resources in lowland peatlands. The results of this study may indicate that forest managers could have increased accessibility to peatland forest resources during the winter months if snowfall is drastically decreased but air temperatures remain below freezing for sufficiently long and consecutive periods.

Although this study found that soil freezing increased under the expected future winter condition of decreased snowfall, most models of climate change in the boreal region and peatlands in particular have estimated that by the end of this century, soil frost days will decrease as a result of increasing wintertime air temperatures. Several large, regional scale models predict that climate change will result in decreased snow cover, fewer soil frost days, and a general decline in the depth of soil frost throughout much of the boreal region (Handler et al., 2014; Kellomäki et al., 2010; Venäläinen et al., 2001; Sinha & Cherkauer, 2010). These models tend to predict that, while snowfall is expected to decrease, average wintertime air temperatures will likely be large enough to counteract the effect of a loss of snow cover on soil frost. Modeled studies at an ecosystem level have attempted to understand how climate change may directly and specifically affect peatlands (Balland et al., 2006; Huang et al., 2017). While these studies have resulted in some advances in understanding potential climate change effects on peatlands, there is still a high level of uncertainty in modeled projections of climate-change impacts on peatland hydrology, particularly in predicting soil frost depth (Balland et al., 2006; Huang et al., 2017). Because of the intrinsic relationship between peatland hydrology and the ecologic functions and economic services they provide, it is imperative that additional study is conducted to better understand how peatlands may react to a changing climate.

Potential Directions for Future Study

This study describes the results from the first two winter seasons of what will likely be a longer-term investigation of the impact of snow removal on soil frost and related phenomena in peatland soils. Future study could investigate gas flux from paired plots, nutrient cycling, changes in DOC, and fine root and/or plant mortality. Observational evidence from this study may indicate that colder soils and prolonged freezing could negatively impact *Sphagnum* moss communities. Additionally, it would be important to know whether increased freezing might affect regeneration of slow-growing tree species, such as black spruce. Understanding how snow removal impacts these and other peatland plant communities is an area in need of study. In addition to plant communities, an understanding of the effect of snow removal on microbial communities would also help advance our understanding of how peatland carbon storage and carbon flux may be affected by deeper and prolonged freezing of peatland soils. Deeper investigation of these factors could provide a better picture of the ecological consequences of decreased snow cover on peatland soils and fill a gap in the existing literature related to how winter processes regulate ecological functioning in these ecosystems.

It would also be important to investigate how additional treatments could affect frost development in peatland soils. Such treatments could include: (1) compaction of the snow cover, similar to how frost is currently propagated by foresters; (2) removal of snow cover for only part of the winter season, while allowing snow to accumulate for only either the first or later part of the season; and/or (3) apply heated air temperatures to certain plots, to mimic projected increases in air temperature over the coming decades. These additional treatments may provide more additional information on how winter dynamics in peatlands may shift and how to manage peatland ecosystems under a changing climate.

Conclusion

Climate change is expected to result in decreased snowfall across much of the boreal zone, including northern Minnesota, by the end of this century. The results of this study indicate that, in the forested peatlands of northern Minnesota, decreased snow cover via snow removal results in significantly colder peatland soils with significantly deeper frost development than under ambient conditions. Both colder soils and increased frost depth were observed across all replicates, although some site-specific differences did exist in the rate and depth of frost generation. Soil temperature was found to be colder and more variable under snow removal conditions across all sites and depths, with the variability primarily attributable to changes in soil temperature in the upper soil profile in reaction to fluctuations in air temperature. Ambient snow cover plots experienced very little variability in soil temperature, with temperatures at or near 0°C across depths for nearly the entire winter season.

While these results indicate that under conditions of decreased snow cover, soil temperature will decrease and frost will increase, additional study is needed to understand how these frost dynamics affect the ecological functioning of peatlands. In addition, this study did not take into account how increased air temperature may interact with decreased snow cover to moderate the effects on soil frost that were seen in this study. Because of this, the impact of climate change on soil frost development in forested peatlands remains uncertain.

References

Balland, V., Bhatti, J., Errington, R., Castonguay, M. & Arp, P.A. (2006). Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). *Canadian Journal of Soil Science, 86,* 203-217. doi:10.4141/S05-088

Bonales, L.J., Rodriguez, A.C., & Sanz, P.D. (2017). Thermal conductivity of ice prepared under different conditions. *International Journal of Food Properties, 20*(1), 610-619. doi:10.1080/10942912.2017.1306551

Cleavitt, N.L., Fahey, T.J., Groffman, P.M., Hardy, J.P., Henry, K.S., & Driscoll, C.T. (2008). Effects of soil freezing on fine roots in a northern hardwood forest. *Canadian Journal of Forest Research, 38*(1), 82-91. doi:10.1139/X07-133

Decker, K.L.M., D. Wang, C. Waite, and T. Scherbatskoy. (2003). Snow removal and ambient air temperature effects on forest soil temperatures in northern Vermont. *Soil Science Society of America Journal*, *67*(4), 1234-1242. doi:10.2136/sssaj2003.1234

Division of Forestry. (2019). *Minnesota's forest resources 2017*. St. Paul, MN: Minnesota Department of Natural Resources. Retrieved from http://files.dnr.state.mn.us/forestry/um/forest-resources-report-2017.pdf

Dunn, A.L., Barford, C.C., Wofsy, S.C., Goulden, M.L., & Daube, B.C. (2007). A long-term record of carbon exchange in a boreal black spruce forest: Means, responses to interannual variability, and decadal trends. *Global Change Biology, 13,* 577-590. doi:10.1111/j.1365-2486.2006.01221.x

Dymond, S.F., Kolka, R.K., Bolstad, P.V., & Sebestyn, S.D. (2014). Long-term soil moisture patterns in a northern Minnesota forest. *Soil Science Society of America Journal, 78*(S1), S208-S216. doi:10.2136/sssaj2013.08.0322nafsc

Edwards, A.C. & Cresser, M.S. (1992). Freezing and its effect on chemical and biological properties of soil. In B.A. Stewart (Ed.), *Advances in Soil Science, Volume 18* (59-79). New York, NY: Springer.

FitzGibbon, J.E. (1981). Thawing of seasonally frozen ground in organic terrain in central Saskatchewan. *Canadian Journal of Earth Sciences, 18*(9), 1492-1496. doi:10.1139/e81-139

Freppaz, M., Celi, L., Marchelli, M., & Zanini, E. (2008). Snow removal and its influence on temperature and N dynamics in alpine soils (Vallée d'Aoste, northwest Italy).

Journal of Plant Nutrition and Soil Science, 171, 672-680. doi:10.1002/jpln.200700278

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S., & Roulet, N. (2011). Peatlands in the Earth's 21st century climate system. *Environmental Reviews, 19,* 371-396. doi:10.1139/A11-014

Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications, 1*(2), 182-195. doi:10.2307/1941811

Groffman, P.M., Hardy, J.P., Nolan, S., Fitzhugh, R.D., Driscoll, C.T., & Fahey, T.J. (1999). Snow depth, soil frost and nutrient loss in a northern hardwood forest. *Hydrological Processes, 13*(14-15), 2275-2286. doi:10.1002/(SICI)1099-1085(199910)13:14/15%3C2275::AID-HYP858%3E3.0.CO;2-A

Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.T., Fitzhugh, R.D., & Tierney, G.L. (2001). Colder soil in a warmer world: A snow manipulation study in a northern hardwood forest ecosystem. *Biogeochemistry, 56*(2), 135-150. doi:10.1023/A:1013039830323

Handler, S., Duveneck, M.J., Iverson, L., Peters, E., Scheller, R.M., Wythers, K.R., Brandt, L., Butler, P., Janowiak, M., Shannon, P.D., Swanston, C., Barrett, K., Kolka, R., McQuiston, C., Palik, B., Reich, P.B., Turner, C., White, M., Adams, C., D'Amato, A., Hagell, S., Johnson, P., Johnson, R., Larson, M., Matthews, S., Montgomery, R., Olson, S., Peters, M., Prasad, A., Rajala, J., Daley, J., Davenport, M., Emery, M.R., Fehringer, D., Hoving, C.L., Johnson, G., Johnson, L., Neitzel, D., Rissman, A., Rittenhouse, C., & Ziel, R. (2014). *Minnesota forest ecosystem vulnerability assessment and synthesis: A report from the Northwoods Climate Change Response Framework project* (Gen. Tech. Rep. NRS-133.) Newtown Square, PA; U.S. Department of Agriculture, Forest Service, Northern Research Station. doi:10.2737/NRS-GTR-133.

Hardy, J.P., P.M. Groffman, R.D. Fitzhugh, K.S. Henry, A.T. Welman, J.D. Demers, T.J. Fahey, C.T. Driscoll, G.L. Tierney, and S. Nolan. (2001). Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. *Biogeochemistry*, *56*(2), 151-174. doi:10.1023/A:1013036803050

Hayashi, M. (2013). The cold vadose zone: Hydrological and ecological significance of frozen‐soil processes. *Vadose Zone Journal*, *12*(4). doi:10.2136/vzj2013.03.0064

Henry, H.A.L. (2008). Climate change and soil freezing dynamics: Historical trends and projected changes. *Climatic Change, 87*(3-4), 421-434. doi:10.1007/s10584-007-9322-8

Hirota, T., Iwata, Y., Hayashi, M., Suzuki, S., & Takayabu, I. (2006). Decreasing soil-frost depth and its relation to climate change in Tokachi, Hokkaido, Japan. *Journal of the Meteorological Society of Japan, 84*(4), 821-833.

Huang, Y., Jiang, J., Ma, S., Ricciuto, D., Hanson, P.J. & Luo, Y. (2017). Soil thermal dynamics, snow cover, and frozen depth under five temperature treatments in an ombrotrophic bog: Constrained forecast with data assimilation. *Journal of Geophysical Research: Biogeosciences, 122*, 2046-2063. doi:10.1002/2016JG003725

Iwata, Y., Hayashi, M., Suzuki, S., Hirota, T., & Hasegowa, S. (2010). Effects of snow cover on soil freezing, water movement, and snowmelt infiltration: A paired-plot experiment. *Water Resources Research, 46*. doi:10.1029/2009WR008070

Joosten, H. & Clarke, D. (2002). *Wise use of mires and peatlands: Background and principles including a framework for decision making*. Saarijärvi, Finland: International Mire Conservation Group and International Peat Society. Retrieved from http://www.gret-perg.ulaval.ca/fileadmin/fichiers/fichiersGRET/pdf/Doc_generale/WUMP_Wise_Use_of_Mires_and_Peatlands_book.pdf

Joosten, H., Tapio-Biström, M.L., & Tol, S. (Eds.). (2012). *Peatlands: Guidance for climate change mitigation through conservation, rehabilitation and sustainable use* (2nd ed.). Rome, Italy: Food and Agriculture Organization of the United Nations & Wetlands International.

Juusela, T. (1967). Some results of field observations on the frost phenomenon on peat soil. *Journal of Hydrology, 5*, 269-278. doi:10.1016/S0022-1694(67)80106-9

Kolka, R., Steber, A., Brooks, K., Perry, C., & Powers, M. (2012). Relationships between soil compaction and harvest season, soil texture, and landscape position for aspen forests. *Northern Journal of Applied Forestry, 29*(1), 21-25. doi:10.5849/njaf.10-039

Kellomäki, S., Maajärvi, M., Strandman, H., Kilpeläinen, A. & Peltola, H. (2010). Model computations on the climate change effects on snow cover, soil moisture and soil frost in the boreal conditions over Finland. Silva Fennica, 44(2), 213-233. Retrieved from http://www.metla.fi/silvafennica/full/sf44/sf442213.pdf

Lenth, R.V. (2016). *Least-squares means: The R package lsmeans*. doi:10.18637/jss.v069.i01.

Limpens, J., Berendse, F., Blodau, C., Freeman, C., Holden, J., Roulet, N., Rydin, H., & Schaepman-Strub, G. (2008). Peatlands and the carbon cycle: From local processes toglobal implications – a synthesis. *Biogeosciences, 5,* 1475-1491. doi:10.5194/bg-5-1475-2008

Minnesota State Climatology Office. (2019). *Minnesota Normal Annual Snowfall: 1981-2010*. Retrieved from https://www.dnr.state.mn.us/climate/summaries_and_publications/normalsportal.html

O'Donnell, J.A., Romanovsky, V.E., Harden, J.W., & McGuire, A.D. (2009). The effect of moisture content on the thermal conductivity of moss and organic soil horizons from black spruce ecosystems in interior Alaska. *Soil Science, 174*(12), 646-651. doi:10.1097/SS.0b013e3181c4a7f8

Pinheiro, J., Bates, D., Debroy, S., Sarkar, D., & R Core Team. (2017). *Nlme: Linear and nonlinear mixed effects models*. Retrieved from https://cran.r-project.org/package-nlme.

Price, D.T., Alfaro, R.I., Brown, K.J., Flannigan, M.D., Fleming, R.A., Hogg, E.H., Girardin, M.P., Lakusta, T., Johnston, M., McKenney, D.W., Pedlar, J.H., Stratton, T., Sturrock, R.N., Thompson, I.D., Trofymow, J.A. & Venier, L.A. (2013). Anticipating the consequences of climate change for Canada's boreal forest ecosystems. *Environmental Reviews, 21* (322-365). doi:10.1139/er-2013-0042

Quinton, W.L., Hayashi, M., & Carey, S.K. (2008). Peat hydraulic conductivity in cold regions and its relation to pore size and geometry. *Hydrological Processes, 22*, 2829-2837. doi:10.1002/hyp.7027

Robroek, B.J.M., Heijboer, A., Jassey, V.E.J., Hefting, M.M., Rouenhorst, T.G., Buttler, A., & Bragazza, L., (2013). Snow cover manipulation effects on microbial community structure and soil chemistry in a mountain bog. *Plant Soil, 369*, 151-164. doi:10.1007/s11104-012-1547-2

Sebestyn, S.D., Dorrance, C., Olson, D.M., Verry, E.S., Kolka, R.K., Elling, A.E., & Kyllander, R., (2011). Long-term monitoring sites and trends at the Marcell Experimental Forest. In Kolka, R.K., Sebestyen, S.D., Verry, E.S., & Brooks, K.N. (Eds.), *Peatland biogeochemistry and watershed hydrology at the Marcell Experimental Forest*. Boca Raton, FL: CRC Press: 15-71.

Seppälä, M. (1990). Depth of snow and frost on a palsa mire, Finnish Lapland. *Geografiska Annaler, Series A, Physical Geography, 72*(2), 191-201. doi:10.2307/521114

Sharratt, B.S., Baker, D.G., Wall, D.B., Skaggs, R.H., & Ruschy, D.L. (1992). Snow depth required for near steady-state soil temperatures. *Agricultural and Forest Meteorology, 57*, 243-251.

Sinha, T. & Cherkauer, K.A. (2010). Impacts of future climate change on soil frost in the midwestern United States. *Journal of Geophysical Research, 115*. doi:10.1029/2009JD012188, 2010

Tierney, G.L., Fahey, T.J., Groffman, P.M., Hardy, J.P., Fitzhugh, R.D., & Driscoll, C.T. (2001). Soil freezing alters fine root dynamics in a northern hardwood forest. *Biogeochemistry*, *56*(2), 175-190. doi:10.1023/A:1013072519889

Turetsky, M.R., Kelman Wieder, R., & Vitt, D.H. (2002). Boreal peatland C fluxes under varying permafrost regimes. *Soil Biology & Biochemistry, 34*, 907-912. doi:10.1016/S0038-0717(02)00022-6

USDA Forest Service. (2007). *Marcell Experimental Forest Data: Frost Metadata*. Retrieved from https://www.nrs.fs.fed.us/ef/marcell/data/metadata/meta_frost/

Venäläinen, A., Tuomenvirta, H., Heikinheimo, M., Kellomäki, S., Peltola, H., Strandman, H., & Väisänen, H. (2001). Impact of climate change on soil frost under snow cover in a forested landscape. *Climate Research, 17*(1), 63-72. Retrieved from http://www.jstor.org/stable/24867344

Wickham, H., François, R., Henry L., & Müller, K. (2019). *dplyr: A Grammar of Data Manipulation*. R package version 0.8.1. https://CRAN.R-project.org/package=dplyr

Woo, M.K. & Winter, T.C. (1993). The role of permafrost and seasonal frost in the hydrology of northern wetlands in North America. *Journal of Hydrology, 141*, 5-31. doi:10.1016/0022-1694(93)90043-9

Xu, J., Morris, P.J., Liu, J. & Holden, J. (2018). PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, *160*, 134-140. doi:10.1016/j.catena.2017.09.010

Yu, Z. (2011). Holocene carbon flux histories of the world's peatlands: Global carbon-cycle implications. *The Holocene, 21*(5), 761-774. doi:10.1177/0959683610386982

Yu, Z., Beilman, D.W., Frolking, S., MacDonald, G.M., Roulet, N.T., Camill, P., & Charman, D.J. (2011). Peatlands and their role in the global carbon cycle. *Eos, 92*(12), 97-108. doi:10.1029/2011EO120001

Zhang, S.Y. & Morgenstern, E.K. (1995). Genetic variation and inheritance of wood density in black spruce (*Picea mariana*) and its relationship with growth: Implications for tree breeding. *Wood Science and Technology, 30*(1), 63-75. doi:10.1007/BF00195269

Appendices

Appendix A:

a) Three-way ANOVA results summary for the soil temperature model showing model coefficient p-values and numerator degrees of freedom for data collected during the spring of 2018.

		Spring 4/28/18 – 6/23/18
Model Term	**numDF**	p-value
Treatment	1	<0.001
Week	8	<0.001
Sensor Depth	5	<0.001
Treatment:Week	8	<0.001
Treatment:Sensor Depth	5	<0.001
Week:Sensor Depth	40	<0.001
Treatment:Week:Sensor Depth	40	0.8234

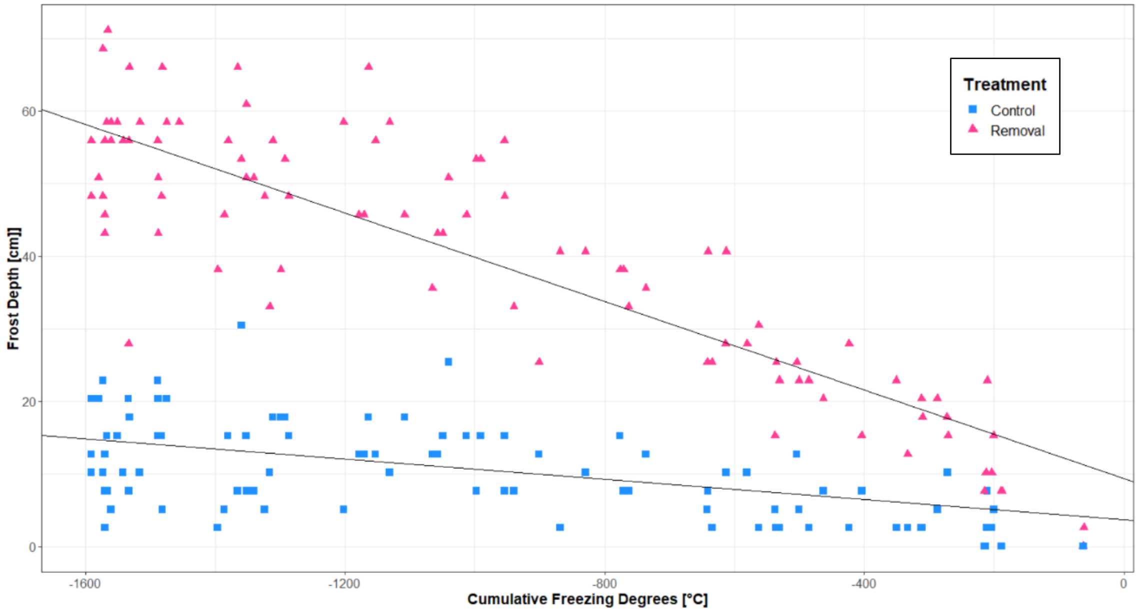
b) Three-way ANOVA results summary for the soil temperature model showing model coefficient p-values and numerator degrees of freedom for data collected during the summer of 2018.

		Summer 6/30/18 – 8/18/18
Model Term	**numDF**	p-value
Treatment	1	<0.001
Week	7	0.0092
Sensor Depth	3	<0.001
Treatment:Week	7	<0.001
Treatment:Sensor Depth	3	<0.001
Week:Sensor Depth	21	<0.001
Treatment:Week:Sensor Depth	21	0.0082

c) Three-way ANOVA results summary for the soil temperature model showing model coefficient p-values and numerator degrees of freedom for data collected during the autumn of 2018.

		Autumn 8/25/18 – 10/13/18
Model Term	**numDF**	p-value
Treatment	1	<0.001
Week	7	0.7172
Sensor Depth	3	<0.001
Treatment:Week	7	<0.001
Treatment:Sensor Depth	3	0.0002
Week:Sensor Depth	21	<0.001
Treatment:Week:Sensor Depth	21	<0.001

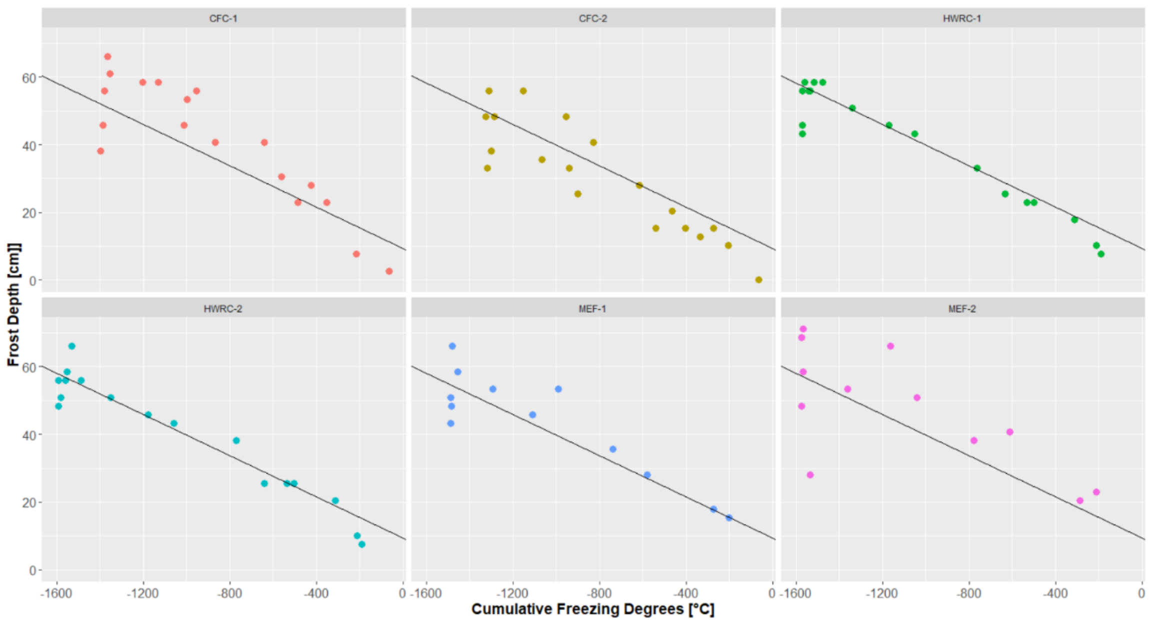
Appendix B:



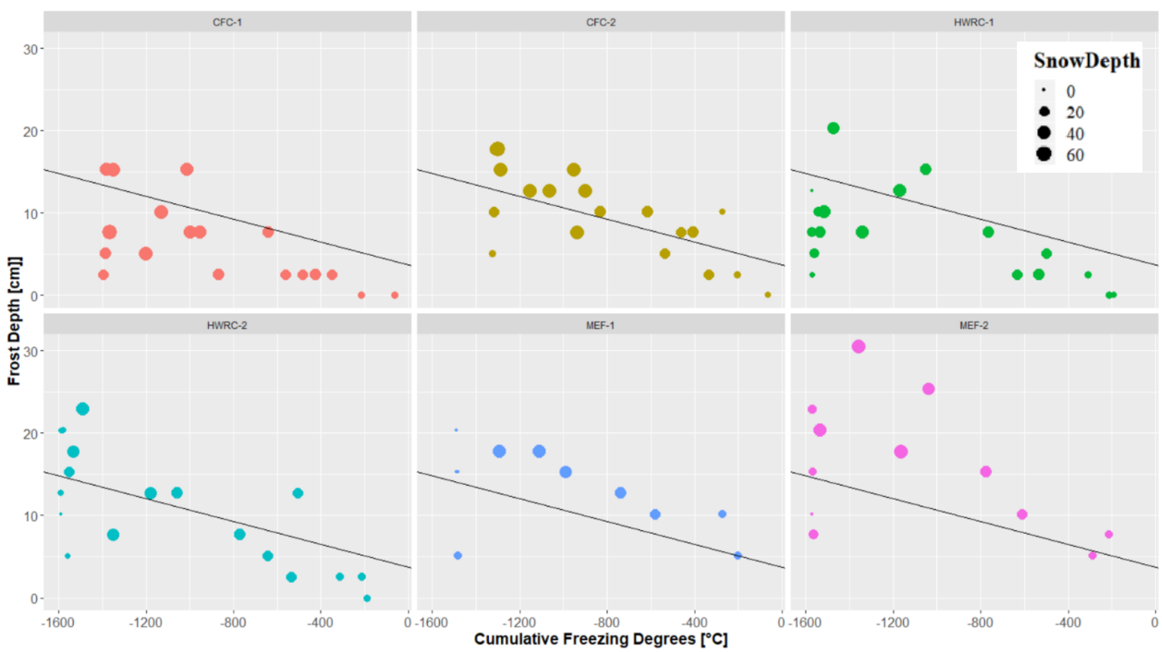
Frost depth as a function of cumulative freezing temperatures during the 2018-2019 winter season. The best-fit linear regression lines for the control and removal plots are shown. In the snow removal plots, the best fit line is described by $y = -0.03x + 9.13$ ($R^2 = 0.68$), while the best fit line for the control plots is described by $y = -0.008x + 2.74$ ($R^2 = 0.33$).

Appendix C:

a)

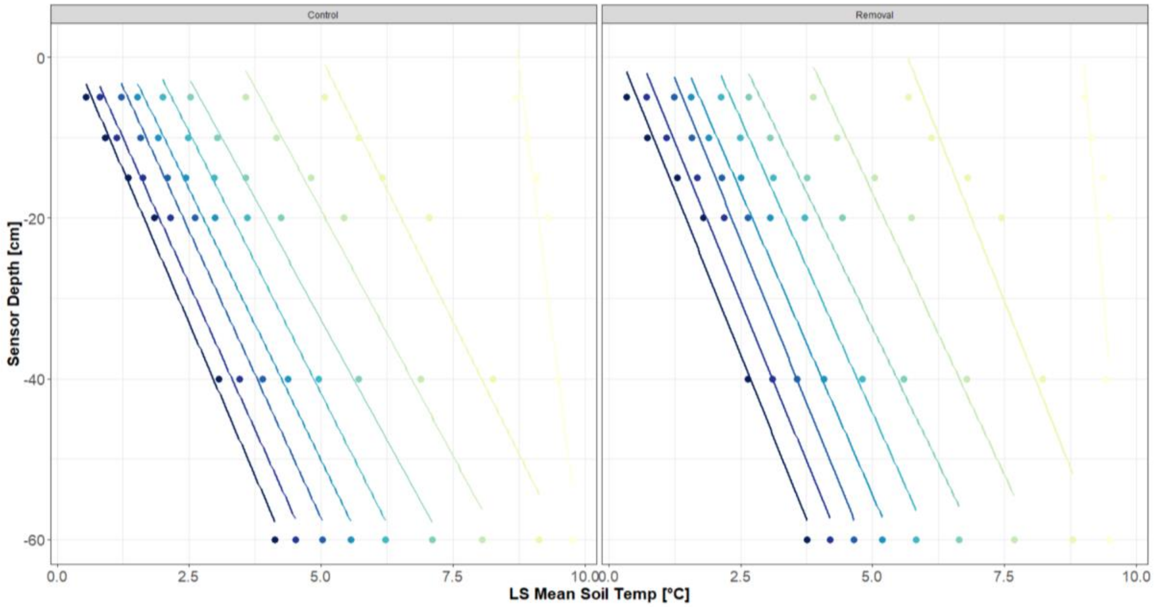


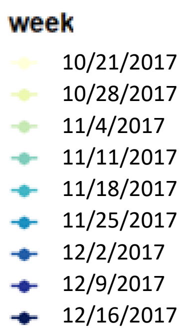
b)



Frost depth as a function of cumulative freezing temperatures during the 2018-2019 winter season divided by site. a) Frost depth as measured by individual site as a function of cumulative freezing temperatures on the snow removal plots. The best fit line for the regression relationship for snow removal is shown. b) Frost depth as measured by individual site as a function of cumulative freezing temperatures on the control plots. The best fit line for the regression relationship for control plots is shown.

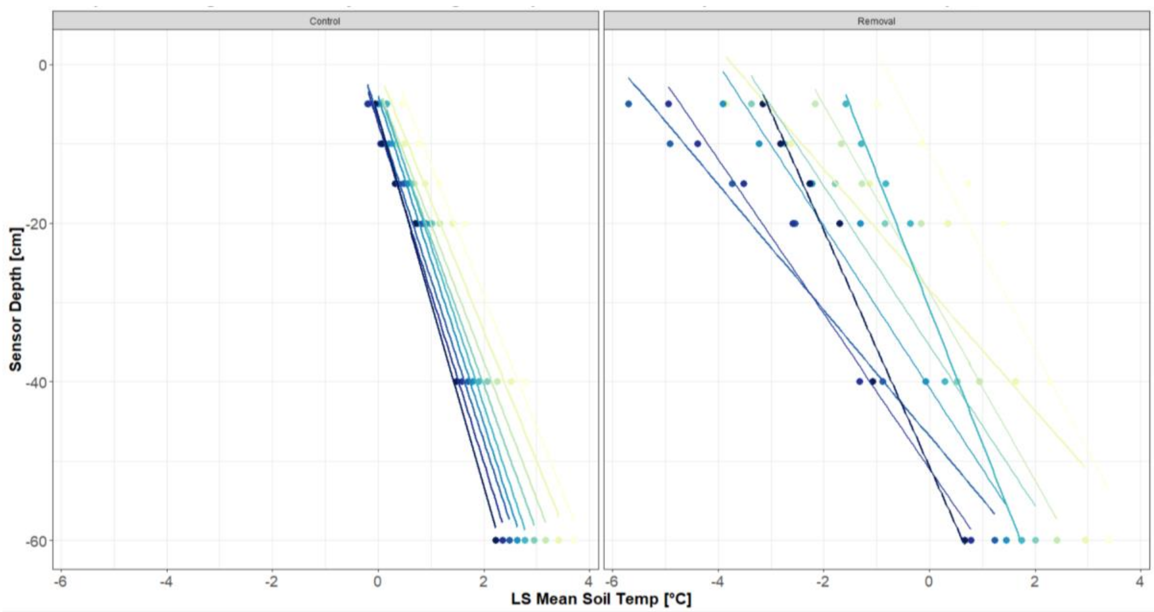
Appendix D:





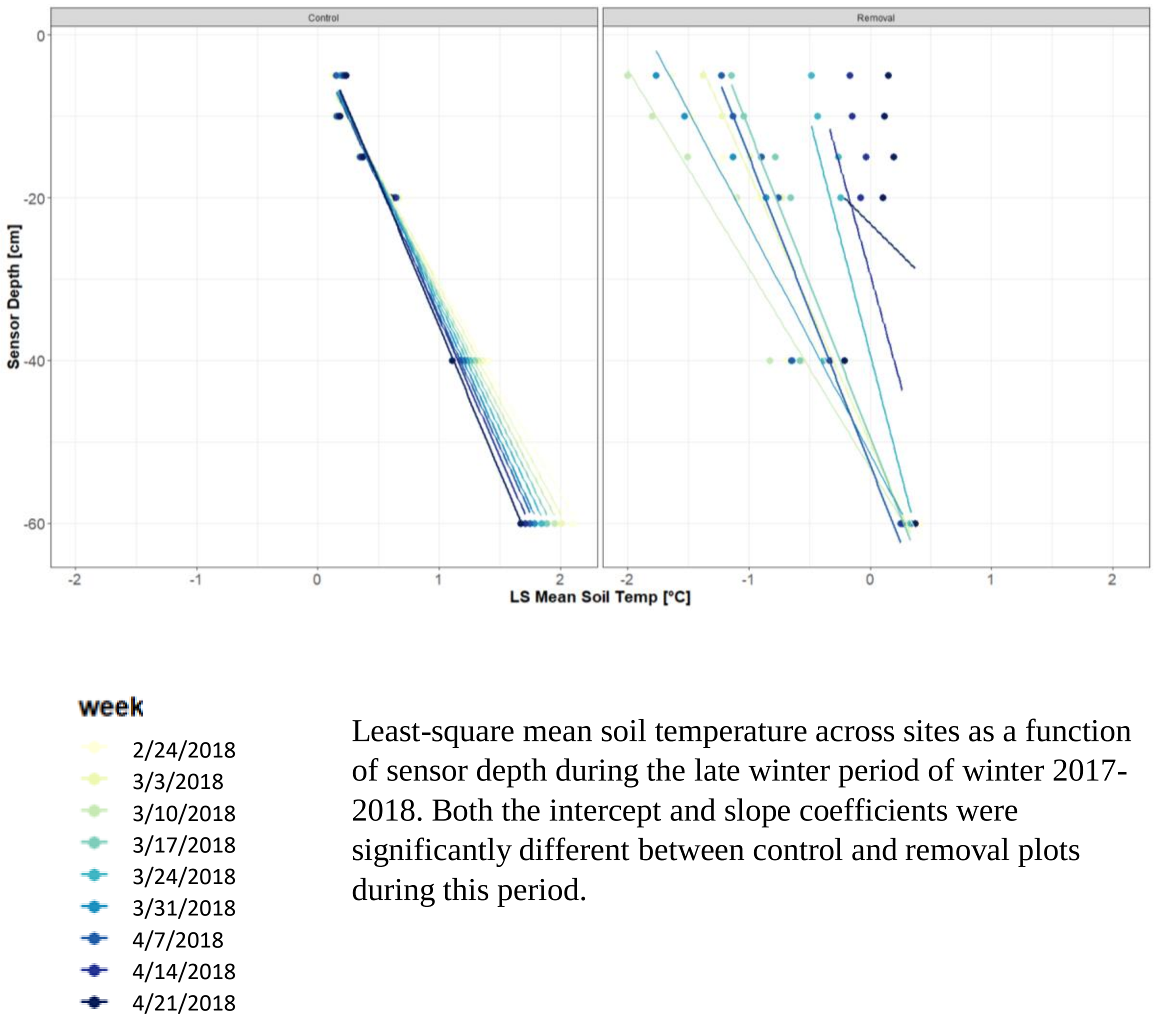
Least-square mean soil temperature across sites as a function of sensor depth during the early winter period of winter 2017-2018. There were no significant differences in intercept or slope coefficient between control and removal plots during this period.

Appendix E:



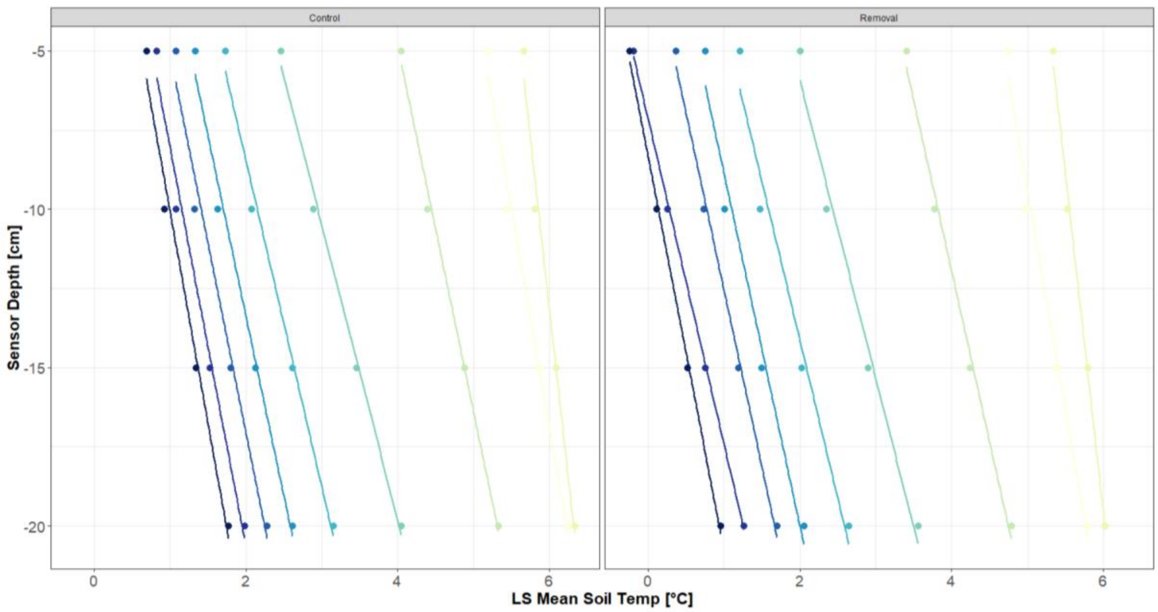
Least-square mean soil temperature across sites as a function of sensor depth during the mid-winter period of winter 2017-2018. Both the intercept and slope coefficients were significantly different between control and removal plots during this period.

Appendix F:



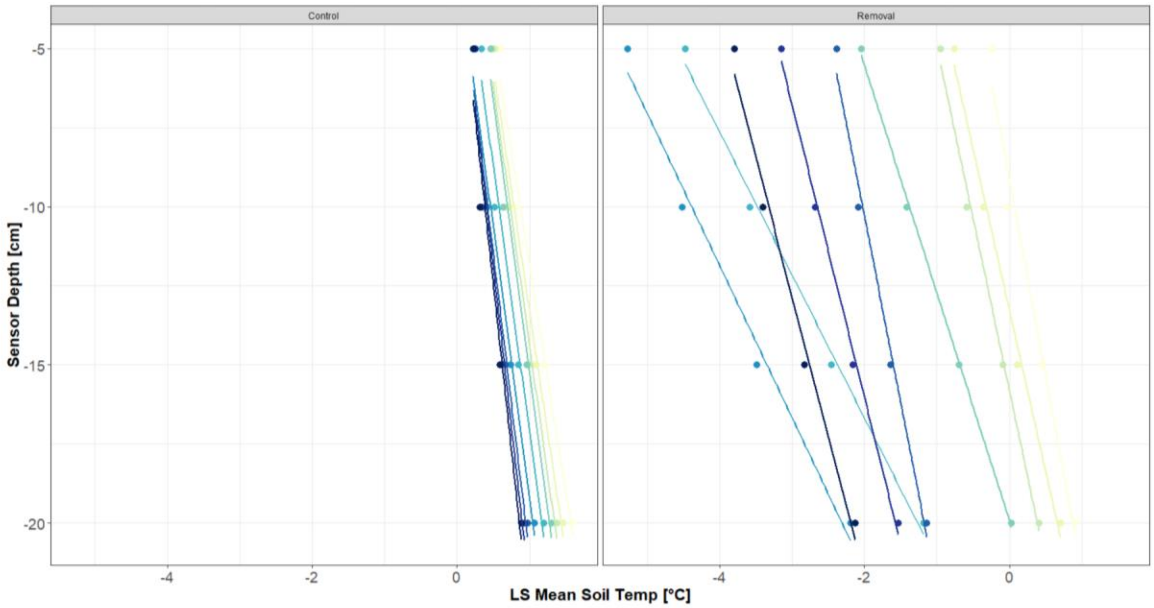
Least-square mean soil temperature across sites as a function of sensor depth during the late winter period of winter 2017-2018. Both the intercept and slope coefficients were significantly different between control and removal plots during this period.

Appendix G:



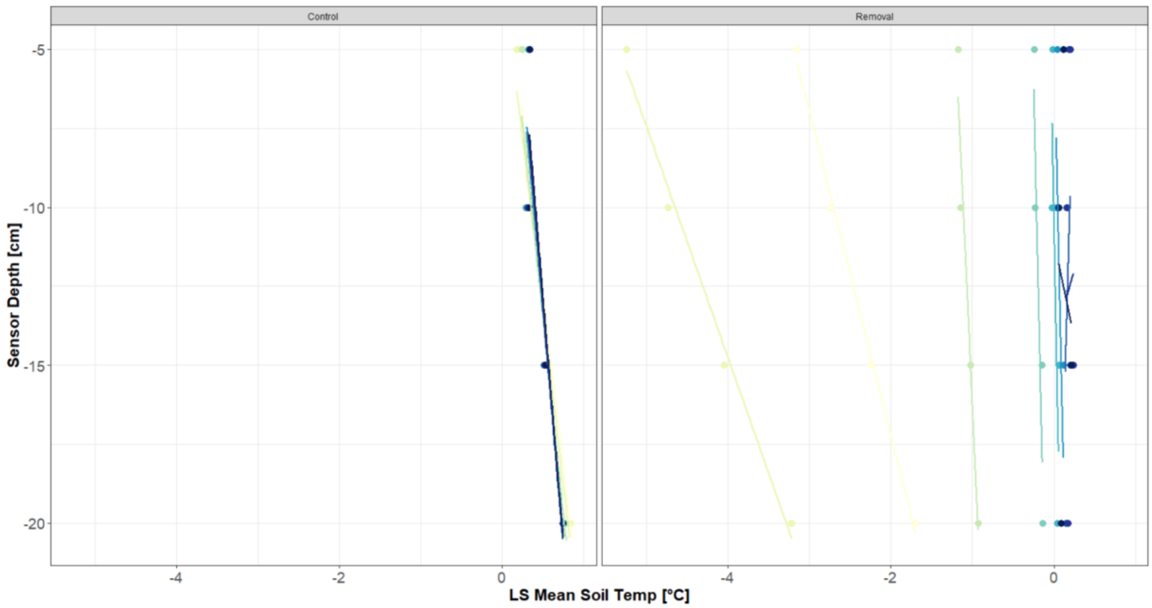
Least-square mean soil temperature across sites as a function of sensor depth during the early winter period of winter 2018-2019. There were no significant differences in intercept or slope coefficient between control and removal plots during this period.

Appendix H:



Least-square mean soil temperature across sites as a function of sensor depth during the mid-winter period of winter 2018-2019. Both the intercept and slope coefficients were significantly different between control and removal plots during this period.

Appendix I:



Least-square mean soil temperature across sites as a function of sensor depth during the late winter period of winter 2018-2019. Both the intercept and slope coefficients were significantly different between control and removal plots during this period.